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MATHEMATICAL MODELS FOR WATER QUALITY FOR THE HUDSON-CHAMPLAIN AND METROPOLITAN COASTAL WATER POLLUTION CONTROL PROJECT

Hydroscience, Incorporated
Leonia, New Jersey

April 1968

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Prepared For
THE FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

MATHEMATICAL MODELS FOR WATER QUALITY FOR THE HUDSON-CHAMPLAIN AND METROPOLITAN COASTAL WATER POLLUTION CONTROL PROJECT

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April 1968

Federal Water Pollution
Control Administration
Raritan Arsenal
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Attention Mr. Paul De Falco

Gentlemen:

In accordance with our Contract No. Ph-86-65-125, we are submitting herewith our final report entitled "Mathematical Models for Water Quality for the Hudson-Champlain and Metropolitan Coastal Water Pollution Control Project." This report presents the development procedures and specific water quality models for the waterways extending from the lock at Troy, New York to the Atlantic Ocean including the Raritan River and New York Harbor Complex.

The mathematical models may provide response functions relating receiving water quality to various inputs of waste water under steady-state conditions. In addition, the models can be employed to evaluate the influence of existing waste discharges on present water quality and to provide a method of testing the effectiveness of alternative pollution abatement and control facilities.

We would like to express our appreciation for the assistance and cooperation of the members of your staff who participated in this project, and in particular to Messrs. Parke, Gritzuk, and Shotwell.

Very truly yours,

John L. Mancini

John L. Mancini

Very truly yours,

Donald J. O'Connor

Donald J. O'Connor

I

ERRATA

Mathematical Models for Water Quality
for the Hudson-Champlain and Metropolitan Coastal
Water Pollution Control Project

Prepared for

The Federal Water Pollution Control Administration

by

Hydroscience Inc.
Leonia, N.J.

April 1968

Page 24	In Equation (8), Q should be -Q
Page 26	In the equation above Equation (12), it should read +RK
Page 31	In Equation (15), W should be multiplied by F
Page 35	In Table 2, under application of Uniform BOD Discharge W, under Deficit Equation, the first DK should be multiplied by F
Page 80	In Equation (46b), YB (I) should be changed to read YD (I)
Page 89	Under Class 11 Boundary Condition, DFORC(J), B (KK) should be multiplied by VOL (KK)
	Under Class 12 Boundary Condition, DFORC(J), AK (KK) should be DK (KK) and B (KK) should be multiplied by VOL (KK)

II

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INTRODUCTION

Water discharges from urban population centers, industries, rural runoff, and storm overflows carry significant quantities of nutrients, organic and inorganic pollution to our waterways. Programs to control water quality invariably require large capital and operating expenditures. Among the specific procedures which have been considered for pollution and water quality control are treatment plant construction, low flow augmentation, transportation of wastes and dispersion in oceans.

It is both desirable and essential that a realistic assessment be obtained of the degree of water quality improvement and control which will actually result from pollution control activities. In addition, economies in capital and operating expenditures can be associated with a systematic evaluation of alternative control procedures considering water quality management on a drainage basin and/or regional basis. It is the purpose of this report to present the mathematical models which will permit an assessment of water quality conditions and the improvements associated with various control procedures.

The mathematical models for water quality presented in this report may provide the basic tools for developing a rational systematic approach to water quality management in the region of concern to the Hudson-Champlain Metropolitan Coastal Project. Specifically, the models may be applied to evaluate the influence of existing sources of pollution on present water quality. In addition, the models will provide a means of evaluating the effectiveness of alternative water quality control procedures. The mathematical models for water quality can be employed to predict the system response in conjunction with optimization techniques, thus delineating the least costly solutions for obtaining desired water quality objectives.

SUMMARY

Mathematical models of water quality and pollution for the various bodies of water encompassed by the study area have been developed and are presented in this report. They include the various phenomena and inputs which affect the quality of the water. The models may be used to evaluate present quality conditions and to predict future conditions. They are particularly useful in assessing alternate methods of improving water quality.

The models for water quality relate the phenomena of advection, reaction, and dispersion in a manner which permits the calculation of concentration profiles for substances which are significant in water quality or pollution studies:

1. Advection is characterized by the fresh water velocity which transports pollutants and other material out of the estuary or stream.
2. Reaction is characterized by the reaction rate which is characteristic of the decay of organic matter, bacteria death rates, and decay of radioactive material. Reactions may act as sources or sinks of material.

3. Dispersion is characterized by the parameter "E". This phenomenon is present, to a significant extent, in tidal bodies of water and represents a spreading of material upstream and downstream from the source of pollution

The three phenomena are taken into account by developing a material balance around a differential element of the stream or estuary. The resultant differential equations for conservative substances, such as chlorides and reactive substances, such as BOD, bacteria die-off, and dissolved oxygen deficit are:

Conservative

$$\frac{\partial \bar{C}}{\partial t} = E \frac{\partial^2 \bar{C}}{\partial x^2} - U \frac{\partial \bar{C}}{\partial x} \qquad (1)$$

Reactive

$$\frac{\partial L}{\partial t} = E \frac{\partial^2 L}{\partial x^2} - U \frac{\partial L}{\partial x} - RK \quad L + Y_b \qquad (2)$$

Dissolved Oxygen Deficit

$$\frac{\partial D}{\partial t} = - E \frac{\partial^2 D}{\partial x^2} + U \frac{\partial D}{\partial x} + AK \cdot D + Y_d \qquad (3)$$

Where:

t = Time
x = Distance
$\overline{\overline{C}}$, L, and D = Concentration of the substances under study
E = Dispersion parameter
U = Fresh water velocity
RK = Removal coefficient
AK = Atmospheric reaeration coefficient
Y_b = Sources and sinks of BOD
Y_d = Sources and sinks of deficit

Assuming steady-state conditions:

Equations (1) to (3) can be integrated to yield:

Conservative

$$\overline{\overline{C}} = \overline{A}e^{(U/E)\cdot x} + \overline{\overline{A}} \tag{4}$$

Reactive

$$L = Be^{S\cdot x} + Ce^{V\cdot x} + YB \tag{5}$$

Dissolved Oxygen Deficit

$$D = Ge^{SD\cdot x} + He^{VD\cdot x} + YD \tag{6}$$

where:

$\overline{A}$, $\overline{\overline{A}}$, B, C, G, and H are constants to be evaluated by consideration of the boundary conditions.

S and V		Contain the parameters U, E, RK
SD and VD		Contain the parameters U, E, AK
YB	=	The particular integral of the BOD source and sink terms
YD	=	The particular integral of the deficit source and sink terms and always includes the BOD solution equation (6)

Equations (4), (5), and (6) are developed on the assumption of constant values of the parameters U, E, RK, and AK. These equations are applicable to any section of an estuary where the assumption of constant parameter values is valid. The estuary must be segmented at locations where the value of a parameter changes, at locations of point waste inputs and at locations of changes in the sources or sinks of material. The appropriate equation (Equation (4), (5), or (6), depending on the substance being studied) is then applied to each of the sections formed by the segmentation process. The unknown coefficients are evaluated by considering the boundary conditions at the junction points of adjacent segments. In effect, the boundary conditions at each junction of sections couples the several segments into a single system interrelated through the values of the appropriate unknown coefficients. Considering the BOD solution as an example, the sections formed by segmentation are coupled into a single system by evaluation of boundary conditions at the junction points between sections. The values of the unknown coefficients B and C in any section will reflect the phenomena occurring in all other sections of the system.

The total number of boundary conditions that must be evaluated in any system is equal to twice the number of segments in the system. There are three classes of boundary condition equations which can be specified. These are:

1. Infinity conditions:

   At locations remote from a waste source, the anticipated BOD and dissolved oxygen deficit attributable to the waste source should approach or be equal to zero. This can be stated mathematically by evaluating the BOD or dissolved oxygen deficit equation, at positive or negative infinity.

2. Concentration equality:

   At the junction of two segments, the BOD and dissolved oxygen deficit calculated by the equation in either segment must be the same. Thus, the profile equation in the upstream segment must equal the profile equation in the downstream segment at the junction of the two segments.

3. Mass balance:

   It is possible to develop a material balance around an element at the junction of two sections. The quantity of BOD and dissolved oxygen deficit entering the element must equal the quantity of BOD and deficit leaving the element.

Proper application of the three general classes of boundary conditions indicated above will generate sufficient equations to evaluate all unknown coefficients.

At every junction of "n" segments (n must be greater than one), a single mass balance equation, and (n - 1) concentration equations can be specified. If one end of a section is not bounded by adjacent segments, the infinity boundary condition may be applied.

Evaluation of the boundary condition equations linking adjacent segments results in a series of simultaneous equations equal to the number of unknown coefficients. It is convenient to arrange these unknown equations into a matrix and employ standard techniques to evaluate each of the unknown coefficients. In order to facilitate setting up the matrix of unknown coefficients, a series of general boundary condition equations have been developed and tabulated in this report. The boundary equations are presented in terms of the elements of the matrix and the forcing functions. All specific boundary condition equations required to mathematize the study area have been included in the tabulation.

Two techniques of presenting the matrix have been employed in this report. In the first instance, the actual elements of the matrix have been presented in standard matrix form. For large systems the matrix is presented in tabular form, defining the general boundary equation which is applicable and the specific section numbers to be employed in the equation.

Three scales of models have been developed for the study area. In the first instance, the component waterways have been divided into subsystems and mathematical models developed for the component water ways. These models contain the maximum number of simplifying assumptions and are relatively small and easy to use. The models for the component waterways which have been developed and transmitted as a part of this study are:

1. North River Model
   - a. North River in the vicinity of New York City
   - b. East River
   - c. Upper New York Harbor
   - d. Harlem River
2. East River Model
   - a. Lower East River, extending from the battery to the Harlem River
   - b. Upper New York Harbor
   - c. Upper East River, extending from the Harlem River into Long Island Sound
3. Arthur Kill Model
   - a. Arthur Kill extending into Raritan Bay
   - b. Newark Bay
   - c. Tidal exchange through Kill Van Kull

4. Raritan River Model

   a. Raritan River from the Fieldville Dam to the confluence of the South River
   b. The South River to the Duhernal Dam
   c. Raritan River to the mouth at Raritan Bay

5. Middle Hudson Estuary Model

   a. Extending from Saugerties, New York to Yonkers, New York

6. Upper Hudson Estuary Model

   a. Extending from the Troy lock to Saugerties, New York

7. Lakes

   a. Local pollution model
   b. Stratified body model
      (1) Continuous in the time dimension
      (2) Segmented in the time dimension
   c. Body of water in geological time sense

The second scale of models developed and presented in this report are for large groupings of component waterways and specifically are for:

1. New York Harbor Complex Model
    - a. Upper East River
    - b. Lower East River
    - c. Harlem River
    - d. Upper New York Harbor
    - e. North River
    - f. Kill Van Kull
    - g. Newark Bay
    - h. Arthur Kill
2. Raritan River Model
3. Hudson Estuary Model

    Extending from Troy lock to Yonkers,
    New York in a single continuous model

The second scale of models should be adequate to evaluate the areas under study for the present. It is, however, anticipated that future growth in the area will result in the requirement for a single water quality model extending from Troy, New York to the Atlantic Ocean, including all of the New York Harbor Complex and the Raritan River. To fill this long-range need of the Hudson-Champlain and Metropolitan Coastal Comprehensive Water Pollution Control Project, a single water quality model is presented in this report.

The various parameters and area relationships for each of the component waterways and segments within the component waterways are tabulated. In addition, the information available on waste loads are presented. All these data must be considered as preliminary estimates which require future verification.

The mathematical models must be developed, programmed, tested, and verified before they can be used to develop water quality projections. These steps include and are defined as:

1. Developed
   - a. Segmentation of system
   - b. Establishment of the specific BOD and deficit matrix of unknown coefficients
   - c. Designation of the functional form of the equation for each specific section
2. Programmed
   - a. Written computer program
   - b. Debugged computer program
3. Tested
   - a. Realistic model response to external inputs such as waste loadings

4. Verified

a. Sensitivity evaluation of the system to changes in the values of parameters, area, et al

b. Establishment of a consistent set of parameters

c. Obtaining agreement between observed and calculated profiles for a satisfactory number of flow and temperature conditions

Table 1 is presented to indicate the state of each model and to specify those procedures required before the mathematical models can be used for predicting water quality.

STATE OF DEVELOPMENT OF THE MATHEMATICAL MODELS

TABLE 1

Model Descriptions	Developed	Programmed	Tested	Verified
Models with simplifying assumptions				
1. North River	X	X	X	-
2. East River	X	X	X	-
3. Arthur Kill	X	X	X	-
4. Raritan River	X	X	X	-
5. Middle Hudson	X	X	X	-
6. Upper Hudson	X	X	X	X
7. Lakes	X	**	**	-
Large Component Models				
1. New York Harbor Complex	X	(X)	(X)	-
2. Raritan River	X	X	X	-
3. Hudson Estuary	X	(X)	-	-
Entire System	X	X	-	-

** No Programs Required

(X)In Progress (FWPCA Project Personnel)

CONCLUSIONS

I. Methods have been presented for developing mathematical models for water quality in complex estuaries and streams. The resultant models can be employed to predict water quality profiles for conservative substances, such as salts and other chemicals, non-conservative substances (when first order reaction kinetics are considered), such as BOD, bacterial dieoff, radio active wastes and thermal pollution, and consecutive reactions, such as dissolved oxygen deficit and the nitrification sequence.

II. Specific water quality models have been developed for the component waterways of the study area:

1. North River
2. East River
3. Arthur Kill
4. Raritan River
5. Middle Hudson Estuary
6. Upper Hudson Estuary
7. New York Harbor Complex

8. Hudson Estuary

9. Entire System

    A. Hudson Estuary

    B. New York Harbor Complex

    C. Raritan River

III. Preliminary estimates of system geometry, parameter values, and waste loads have been developed and are tabulated in this report.

IV. The models have been tested employing the parameter estimates.

V. Mathematical models for lakes have been developed considering lakes as:

1. Completely mixed bodies in a large time scale, measured in years.

2. A two-layer system of bottom sediment and liquid surface volume in a large time scale in years.

3. As a thermally stratified body with stratification alternating with time of year, measured in months.

4. A two-layered system defined by a thermocline where the top and bottom liquid volumes change on a time scale of days, weeks, or months.

5. Local lake pollution from outfalls or rivers.

RECOMMENDATIONS

I. A program should be developed which allows interplay between the development of the mathematical models and data collected in field surveys. The objective of the program is to develop a consistent set of system parameters for the mathematical model. This will lead to a verified mathematical model for water quality which can be employed to generate realistic predictions of water quality and evaluate alternative methods of obtaining desired quality objectives.

II. Specific areas requiring additional evaluation are indicated with emphasis placed on the quantity and characteristics of waste water discharges and data on the various components of the total nitrogen in waste discharges and receiving waters.

III. Several specific methods have been suggested for upgrading the usefulness of existing observed water quality data. This includes averaging observations obtained under the same temperature conditions and locating historical observed water quality data with respect to the tidal cycle.

IV. Types of measurements in the lake environment are suggested which will provide a first step to meaningful evaluation of water quality trends and cause and effect relationships.

THEORY

Mathematical models for water quality relate the phenomena of advection, reaction, and dispersion in a manner which permits the calculation of concentration profiles for substances which are measures of pollution or are themselves pollutants.

1. Advection is characterized by the fresh water velocity, "U" which tends to transport pollutants and other material out of the estuary or stream.
2. Reaction is characterized by the reaction rate, "K" which is characteristic of the decay of organic matter, bacteria death rates, and decay of radioactive material. Normally, first order reaction kinetics are assumed.
3. Dispersion is characterized by the parameter "E". This phenomenon is present, to a significant extent, in tidal bodies of water and represents a spreading of material upstream and downstream, tending to diffuse the material uniformly in the vicinity of the source.

The three phenomena are combined by developing a material balance around a differential element of the stream or estuary. In addition, sources and sinks of the material are included.

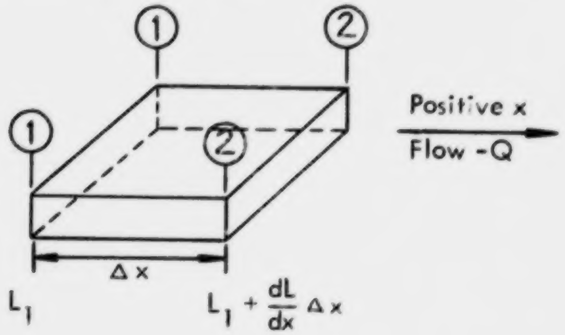
Two sets of nomenclature have been employed in this report. One notation system is for streams and estuaries and a separate system has been developed for lakes. A nomenclature listing for both sets of symbols is presented at the end of this report.

Development of Water Quality Equations

Streams

The phenomenon occurring in a stream can be related by considering a mass balance around a differential element.

BOD with upstream load:



A mass balance is obtained over the time interval Δt. The buildup in the element is evaluated from a consideration of the material entering and leaving through advective transport. The contributions of sources and sinks of material within the element are also included in the inventory.

Mass Balance:

$$\text{Entering element} = Q_1 L_1$$

$$\text{Leaving element} = Q_2 \left(L_1 + \frac{dL}{dx} \Delta x \right)$$

$$\text{Sink} = V \cdot L \cdot RK$$

Equation:

$$\frac{\partial L}{\partial t} = Q_1 L_1 - Q_2 (L_1 + \frac{\partial L}{\partial x} \Delta x) \ RK \cdot L \cdot V \qquad (7)$$

$$Q = Q_1 = Q_2 \text{ and } A_1 = A_2$$

and divide by elemental volume $A \Delta x$

$$\frac{\partial L}{\partial t} = \frac{Q}{A} \frac{\partial L}{\partial x} - RK \cdot L \qquad (8)$$

at steady-state $\frac{\partial L}{\partial t} = 0$

$$0 = - \frac{Q}{A} \frac{dL}{dx} - RK \cdot L$$

$$Q / A = U$$

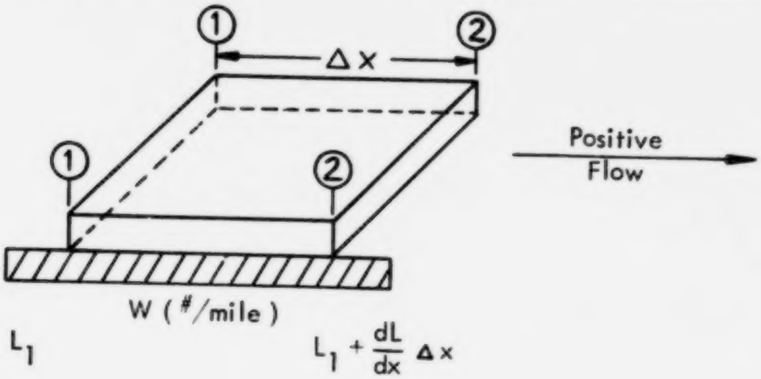
$$0 = - U \frac{dL}{dx} - RK \cdot L \qquad (9)$$

The general solution is :

$$L = Ce \ (- \frac{RK}{U}) \ x \qquad (10)$$

C = constant to be evaluated

BOD when a uniform discharge is in region of the element :


①
②
Δx
①
②
Positive
Flow
W (#/mile)
L_1
$L_1 + \frac{dL}{dx} \Delta x$

Mass Balance :

$$\text{Entering element} = Q_1 L_1$$

$$\text{Leaving element} = Q_2 \left(L_1 + \frac{dL}{dx} \Delta x \right) + V \cdot L \cdot RK$$

$$\text{Source} = W \Delta x$$

Equation :

$$\frac{\partial L}{\partial t} = Q_1 L_1 + W \Delta x - Q_2 \left(L_1 + \frac{\partial L}{\partial x} \Delta x \right) - RK \cdot L \cdot V \qquad (11)$$

$$\frac{\partial L}{\partial t} = 0 \text{ (steady-state)}$$

$$Q = Q_1 = Q_2 \text{ and } A_1 = A_2$$

Equation (11) reduces to :

$$0 = -Q\frac{dL}{dx}\Delta x - RK \cdot L \cdot V + W\Delta x$$

Divide by volume = $V = \Delta x \cdot A$

$$0 = -\frac{Q}{A}\frac{dL}{dx} - (RK) \cdot L + \frac{W}{A}$$

$$\frac{W}{A} = U\frac{dL}{dx} - RK \cdot L$$

The general solution is :

$$L = Ce\left(-\frac{RK}{U}\right)x \qquad (12)$$

C = constant to be evaluated

The particular integral which must be added to Equation (12) is obtained by assuming the form of the particular integral :

$$yp = z$$

$$\begin{array}{r|l} U & \frac{dL}{dx} = 0 \\ RK & L = +RKz \\ \hline \end{array}$$

$$U \frac{dL}{dx} + RK \cdot L = RK \cdot z \equiv \frac{W}{A}$$

$$z = \frac{W}{A \cdot RK}$$

$$yp = \frac{W}{A \cdot RK}$$

$$L = Ce \left(- \frac{RK}{U} \right) x + \frac{W}{A \cdot RK} \qquad (13)$$

Equation (13) is the general solution for the BOD profile in a stream in the vicinity of a uniform waste input of " W " (pounds / mile) .

In the above development, the rate of BOD removal was defined by the parameter " RK " . In a natural body of water, the rate of BOD removal does not necessarily equal the rate at which oxygen is utilized to satisfy the BOD. If organic matter, having a BOD, is removed by sedimentation, stripping, or other physical means, oxygen is not consumed in this removal of BOD. Since these phenomena can occur, it is necessary to employ a parameter in the dissolved oxygen material balance which indicates the rate at which oxygen is utilized to satisfy BOD. This parameter is defined as " DK ". The parameter " DK " can be equal to, or less than the parameter " RK ".

The rate at which oxygen is utilized is equal to the product of the parameter " DK " and the ultimate BOD present. For convenience of computation, the ratio of the ultimate BOD to the five-day BOD is defined by the factor "F", subscripted for the particular waste.

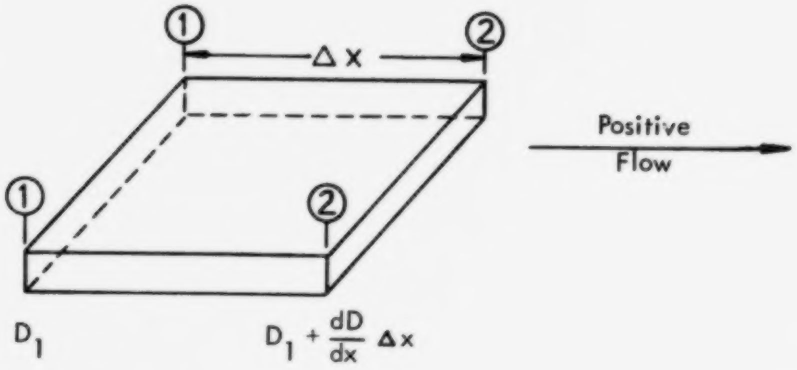
Dissolved Oxygen

Oxygen is soluble in water to a limited extent, being directly related to the partial pressure of oxygen in the atmosphere. The saturation value of oxygen is primarily a function of salinity and temperature. The difference between the saturation concentration and the actual concentrations of oxygen is defined as the dissolved oxygen deficit.

Dissolved oxygen in natural waters can be employed to satisfy the oxygen demand of pollutants, as measured by the BOD. As the oxygen concentration is reduced below the saturation level, the deficit is made up by atmospheric oxygen going into solution. This phenomenon is termed atmospheric reaeration. It occurs at a rate equal to the product of the dissolved oxygen deficit and the reaeration coefficient, "AK".

The differential equation defining dissolved oxygen deficit may be developed by constructing a material balance around a differential element and including the various sources and sinks of dissolved oxygen within the volume.

The material balance is developed incorporating the assumptions that velocity and concentration are uniform across the cross-sectional area of the stream.



The dissolved oxygen deficit balance is constructed in a similar fashion to the BOD . A balance is made between the amounts entering, leaving, and any sources or sinks within the element.

Mass Balance :

$$\text{Entering element} = Q_1 D_1$$

$$\text{Leaving element} = Q_2 \left(D_1 + \frac{dD}{dx} \Delta x \right)$$

$$\text{Sink} = DK \cdot Lx \cdot V$$

$$\text{Source} = AK \cdot D_1 \cdot V$$

Equation at steady-state:

$$0 = -Q \frac{dD}{dx} \Delta x + DK \cdot Lx \cdot V - AK \cdot D_1 \cdot V$$

$$DK \cdot Lx \cdot V = Q\frac{dD}{dx}\Delta x + AK \cdot D \cdot V$$

Divide by volume = $V = A \cdot \Delta x$

$$DK \cdot Lx = \frac{Q}{A}\frac{dD}{dx} + AK \cdot D$$

$$DK \cdot Lx = U\frac{dD}{dx} + AK \cdot D$$

The quantity " Lx " is the ultimate BOD concentration at any point, and is obtained from the BOD solution.

$$Lx = F \cdot Ce^{(-RK/U)x}$$

General solution :

$$0 = U\frac{dD}{dx} + AKD$$

$$D = Ge^{(-AK/U)x}$$

Particular solution :

$$yp = \frac{DK \cdot F}{AK-RK} Ce^{(-\frac{RK}{U})x}$$

Therefore :

$$D = Ge^{(-AK/U)x} + \frac{DK \cdot F}{AK-RK} Ce^{(-RK/U)x} \qquad (14)$$

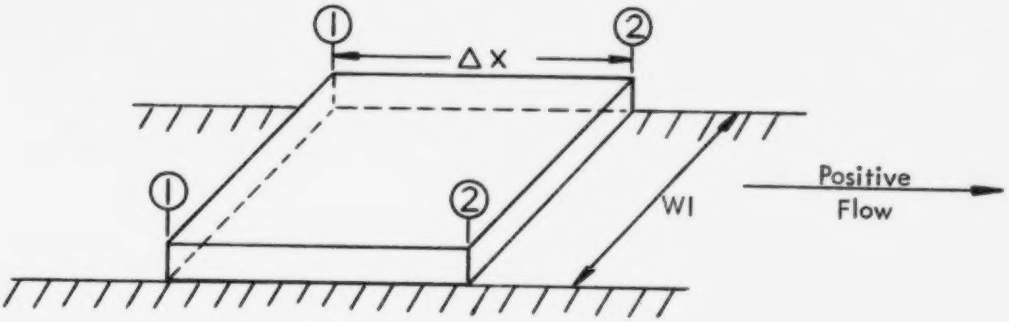
Note that the general form of the deficit solution in streams is :

$$D = Ge^{(-AK/U)x} + \frac{DK \cdot F}{AK - RK} \text{ (BOD solution)}$$

The solution for the deficit profile when uniform loads are considered is :

$$D = Ge^{(-AK/U)x} + \frac{DK \cdot F}{AK - RK}\left(Ce^{(-RK/U)}\right) + \frac{DK}{AK}\left(\frac{W}{RK \cdot A}\right) \quad (15)$$

Bottom deposits in streams



$B\,\# / MI^2 / \text{day}$

$D_1 + \frac{dD}{dx}\,\Delta x$

Mass Balance :

$$\text{Entering element} = D_1 Q_1$$

$$\text{Leaving element} = Q_2\left[D_1 + \frac{dD}{dx}\,\Delta x\right]$$

$$\text{Source} = B \cdot \Delta x \cdot WI$$

$$\text{Sink} = AK \cdot D \cdot V$$

Equation at steady-state :

$$0 = -Q\frac{dD}{dx}\Delta x - AK \cdot D \cdot V + B \cdot \Delta x \cdot WI$$

Dividing by volume : NOTE :

$$\frac{\Delta x \cdot WI}{\Delta x \cdot A} = HT \quad (\text{ where } HT = \text{ water depth })$$

$$0 = -\frac{Q}{A}\frac{dD}{dx} - AK \cdot D + \frac{B}{H_T}$$

$$0 = -U\frac{dD}{dx} - AK \cdot D + \frac{B}{H_T}$$

General Complementary solution :

$$Y_c = Ge^{(-\frac{AK}{U})x}$$

It may be shown that the particular solution is :

$$Y_p = \frac{B}{H_T AK}$$

Therefore:

$$D = Ge^{(-AK/U)x} + \frac{B}{H_T AK} \qquad (16)$$

Algae can influence the dissolved oxygen deficit profile. A daily cycle of algae respiration and oxygen production can be approximated by a constant respiration rate, " R ", and an average daily photosynthesis rate of oxygen production, " P " . The units of " R " and " P " are the mass of oxygen used or produced per day per unit volume. Considering the phenomena of algae utilization and production of oxygen the following analysis may be made again, employing a mass balance around a differential element.

Mass Balance :

Entering element = QD

Leaving element = $Q\left(D + \frac{dD}{dx}\Delta x\right)$

Source = $R \cdot V$

Sink = $AK \cdot D \cdot V + P \cdot V$

Equation for steady-state :

$$0 = -Q\frac{dD}{dx}\Delta x - AK \cdot D \cdot V + R \cdot V - P \cdot V$$

Dividing by volume :

$$0 = -U\frac{dD}{dx} - AK \cdot D + (R - P)$$

$$Y_c = Ge^{(-AK/U)x}$$

$$Y_p = \left(\frac{R - P}{AK}\right)$$

$$D = Ge^{(-AK/U)x} + \frac{R - P}{AK} \qquad (17)$$

Table 2 presents a summary of the general equations for streams to determine the profiles of reactive substances such as BOD and dissolved oxygen deficit.

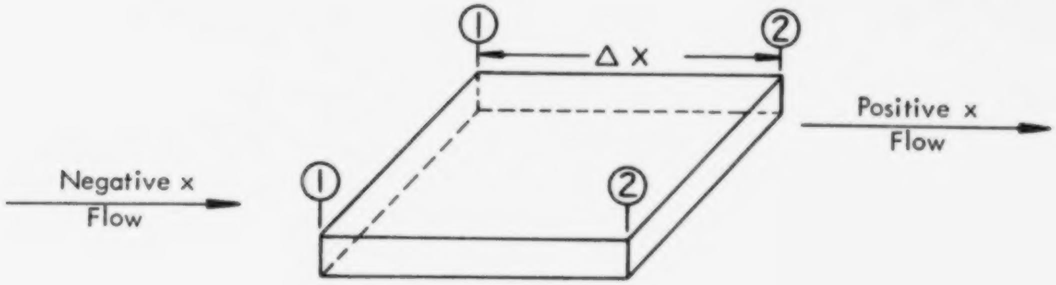
TABLE 2

SUMMARY OF EQUATIONS FOR STEADY - STATE STREAM ANALYSIS

Application	BOD Equation	Deficit Equation
Upstream Load	$L = Ce^{(-RK/U)x}$	$D = Ge^{(-AK/U)x} + \frac{DK \cdot F}{AK - RK}$
Bottom oxygen demand in section (#/ft^2/day)		$D = Ge^{(-AK/U)x} + \frac{B}{H_T \cdot AK}$
Uniform BOD discharge W (# / day / mile) in the section	$L = Ce^{(-RK/U)x} + \frac{W}{A \cdot RK}$	$D = Ge^{(-AK/U)x} + \frac{DK}{AK-RK}\left[Ce^{(-RK/U)x}\right] + \frac{DK}{AK}\left[\frac{W \cdot F}{RK \cdot A}\right]$
Algae in section		$D = Ge^{(-AK/U)x} + \frac{(R-P)}{AK}$

Estuaries:

The equations for evaluation of water quality in estuary systems can be developed in a manner comparable to that which is employed for streams. A differential element is considered and a mass balance is developed. The mass balance includes the phenomena of advection, reaction, reaeration, and in the case of the estuary, diffusion is also included in the inventory.



V_t = Tidal velocity

Mass Balance :

Entering element :

$$C\,(Q + V_t \cdot A) - EA\frac{d}{dx}\left(\frac{dC}{dx}\right) + AK \cdot \left[C_s - C\right] \cdot V$$

Leaving element :

$$C\left[Q + V_t \cdot A\right]\left[C + \frac{dc}{dx}\,\Delta x\right] - EA\,\frac{d}{dx}\left[\frac{dc}{dx} + \frac{dc}{dx}\,\Delta x\right] + DK \cdot L_x \cdot V$$

NOTE: On pages 36 and 37 C is temporarily defined as the dissolved oxygen concentration.

Source : $DK \cdot L_x \cdot V$

Sink : $AK \cdot \left[Cs - C \right] \cdot V$

Equation at steady-state :

$$0 = (-Q + V_t \cdot A) \frac{dc}{dx} \Delta x + EA\Delta x \frac{d^2c}{dx^2} DK \cdot L_x \cdot V + AK \left[Cs - C \right] \cdot V$$

Divide by volume :

$$0 = -(U + V_t) \frac{dc}{dx} + E \frac{d^2c}{dx} - DK \cdot L_x + AK \left[Cs - C \right]$$

The dissolved oxygen deficit is defined as :

$$D = \left[Cs - C \right]$$

$$C = \left[Cs - D \right]$$

and :

$$\frac{dc}{dx} = \frac{-dD}{dx}$$

$$\frac{d^2c}{dx^2} = -\frac{d^2D}{dx^2}$$

Substituting:

$$0 = (U + V_t) \frac{dD}{dx} - E \frac{d^2D}{dx^2} - DK \cdot L_x + AK \cdot D$$

At slack, or if the tidal velocity is averaged over a tidal cycle,

$V_t = 0$. Therefore :

$$DK \cdot L_x = -E\frac{d^2D}{dx^2} + U\frac{dD}{dx} + AK \cdot D$$

$$D = Yc + Yp$$

$$Yc = Ge^{SDX} + He^{VDX}$$

From the quadratic solution :

$$SD = \frac{U}{2E}\left[1 + \left[1 + \frac{4AK \cdot E}{U^2}\right]^{1/2}\right]$$

$$VD = \frac{U}{2E}\left[1 - \left[1 + \frac{4AK \cdot E}{U^2}\right]^{1/2}\right]$$

Using the techniques and reasoning comparable to that employed in the stream development, it may be demonstrated that :

$$Yp = \frac{DK \cdot F}{AK - RK}\left[\text{BOD solution}\right]$$

Therefore, the general equation for the dissolved oxygen deficit profile in an estuary is :

$$D = Ge^{SDX} + He^{VDX} + \frac{DK \cdot F}{AK - RK}\left[\text{BOD solution}\right] \qquad (18)$$

The identical development and reasoning applies to the method of developing differential equations for conservative substances such as chlorides and reactive substances such as BOD .

In the case of the reactive substances such as BOD, the value of AK is zero. Thus the differential equation reduces to :

$$0 = E\frac{d^2L}{dx^2} - U\frac{dL}{dx} - RKL$$

which integrates to :

$$L = Be^{SX} + Ce^{VX} \qquad (19)$$

where:

$$S = \frac{U}{2E}\left[1 + \left[1 + \frac{4RKE}{U^2}\right]^{1/2}\right]$$

$$V = \frac{U}{2E}\left[1 - \left[1 + \frac{4RKE}{U^2}\right]^{1/2}\right]$$

For conservative substances such as chloride the reaction rate is zero and the differential equation reduces to :

$$0 = E\frac{d^2S}{dx} - U\frac{dS}{dx}$$

Root 1 = 0

Root 2 = U/E

The resultant equation is :

$$\bar{\bar{C}} = \bar{\bar{A}}e^{(U/E)x} + \bar{A} \qquad (20)$$

The coefficients $\bar{A}$ and $\bar{\bar{A}}$ can be evaluated from a consideration of the boundary conditions.

Considering the presence of a uniform BOD input entering the section of the estuary system under consideration, the differential equation defining the BOD profile at steady-state becomes :

$$0 = E\frac{d^2L}{dx^2} - U\frac{dL}{dx} - RK \cdot L + \frac{W}{A}$$

$$-\frac{W}{A} = E\frac{d^2L}{dx^2} - U\frac{dL}{dx} - RK \cdot L$$

$$L = Yc + Yp$$

$$Yc = Be^{SX} + Ce^{VX}$$

Yp is evaluated employing the identical techniques as demonstrated in the section dealing with streams.

$$Yp = \frac{W}{A \cdot RK}$$

Therefore:

$$L = Be^{SX} + Ce^{VX} + \frac{W}{A \cdot RK}$$

The influence of algae and bottom deposits on the dissolved oxygen deficit can be evaluated by repeating the techniques employed in the development of the deficit equations for streams. The resultant differential equation is :

$$0 = -E\frac{d^2D}{dx^2} + U\frac{dD}{dx} + AK \cdot D - \frac{BU}{HT} - (R - P)$$

$$\frac{BU}{HT} + (R-P) = -E\frac{dD^2}{dx^2} + U\frac{dD}{dx} + AK \cdot D$$

$$D = Yc + Yp$$

$$Yc = Ge^{SDX} + He^{VDX}$$

It may be demonstrated that Yp must be equal :

$$Yp = \frac{BU}{HT \cdot AK} + \frac{(R-P)}{AK}$$

$$D = Ge^{SDX} + He^{VDX} + \frac{BU}{HT \cdot AK} + \frac{(R-P)}{AK} \qquad (22)$$

Equation (22) may be employed when B or (P - R) are equal to zero. It is possible to further generalize equation (22) by considering a section where there are algae effects, bottom deposits with an oxygen demand, and a uniform BOD input. Considering the above sources of dissolved oxygen and sinks of dissolved oxygen, the resultant steady-state differential equation is:

$$0 = -E\frac{d^2D}{dx^2} + U\frac{dD}{dx} + AK\cdot D - \frac{BU}{HT} - (R-P) - DK\cdot L_x$$

where:

$$L_x = \left[Be^{SX} + Ce^{VX} + \frac{W}{RK\cdot A} \right]\cdot F$$

$$D = Yc + Yp$$

$$Yc = Ge^{SD\cdot X} + He^{VD\cdot X}$$

$$Yp = \frac{DK\cdot F}{AK-RK}\left[Be^{SX} + Ce^{VX}\right] + \frac{DK\cdot W\cdot F}{AK\cdot RK\cdot A} + \frac{B}{HT\cdot AK} + \frac{R-P}{AK}$$

substituting :

$$D = Ge^{SDX} + He^{VDX} + \frac{BU}{HT\cdot AK} + \frac{(R-P)}{AK} + \frac{DK\cdot W\cdot F}{AK\cdot RK\cdot A} + \frac{DK\cdot F}{AK-RK}\left[Be^{S\cdot X} + Ce^{V\cdot X}\right] \tag{23}$$

Table 3 presents a summary of the applicable equations for constant cross-sectional area estuaries for several loading conditions and phenomena which normally influence water quality in an estuary.

TABLE 3

SUMMARY OF EQUATIONS FOR STEADY - STATE SECTION ESTUARY ANALYSIS

Application	First Order Reacting Substances	Dissolved Oxygen Deficit
Upstream or downstream load	$L = Be^{SX} + Ce^{VX}$	$D = Ge^{SDX} + He^{VDX} + [\frac{DK \cdot F}{AK-RK}][Be^{SX} + Ce^{VX}]$
Upstream or downstream load with bottom oxygen demand, algae		$D = Ge^{SDX} + He^{VDX} + \frac{BU}{HT-AK} + \frac{RA-P}{AK}$
Uniform BOD load W (#/day/mi) in section	$L = Be^{SX} + Ce^{VX} + \frac{W}{A \cdot RK}$	$D = Ge^{SDX} + He^{VDX} + [\frac{DK \cdot F}{AK-RK}][Be^{SX} + Ce^{VX}] + \frac{DK \cdot W \cdot F}{AK \cdot RK \cdot A}$
Upstream or downstream load with uniform BOD load, algae & bottom deposit in the section	$L = Be^{SX} + Ce^{VX} + \frac{W}{A \cdot RK}$	$D = Ge^{SDX} + He^{VDX} + \frac{BU}{HT\ \ AK} + \frac{RA-P}{AK} + \frac{DK \cdot W \cdot F}{AK \cdot RK \cdot A} + \frac{DK \cdot F}{AK-RK}[Be^{SX} + Ce^{VX}]$

Estuaries With Variable Cross-Sectional Areas

The material balances obtained around a differential element in a non-stratified estuary have been employed to develop the differential equations describing the concentration profile of polluting substances in estuaries. The estuary configuration assumed in the previous developments was that of a constant cross-sectional area in the direction of flow. Many estuaries are characterized by an expanding area in the downstream direction. Three (3) formulas which have found application as approximations for the rate of increase in cross-sectional areas as a function of distance are:

$$A = Ao\,e^{Qx} \qquad (24)$$

$$A = Ao\left(\frac{R}{Ro}\right) \qquad (25)$$

$$A = Ao\left(\frac{R}{Ro}\right)^{2} \quad \text{or} \quad Ao\left(\frac{R}{Ro}\right)^{n} \qquad (26)$$

The distances R and Ro are from a hypothetical origin at which the cross-sectional area is zero. As examples of the application of expanding area estuaries, one can consider the upper East River and the Raritan River. The upper East River is characterized by the area function, Equation (26), and portions of the Raritan River are characterized by the area function, Equation (25).

Application of the principles of continuity and mass balance results in equations which describe the concentration profiles for both conservative and non-conservative substances.

The upper East River which is characterized by the area function in Equation (26) has no significant fresh water flow. The differential equation which results from a material balance at steady-state conditions is :

BOD :

$$0 = E\frac{d^2L}{dR^2} + \frac{E}{R}\frac{dL}{dR} - RK \cdot L$$

DEFICIT :

$$0 = E\frac{d^2D}{dR^2} + \frac{E}{R}\frac{dD}{dR} - AK \cdot D + DKL_x$$

Integration of these equations results in :

BOD :

$$L = \frac{B}{R}e^{SR} + \frac{C}{R}e^{VR}$$

DEFICIT :

$$D = \frac{G}{R}e^{SDR} + \frac{H}{R}e^{VDR} + \frac{DK \cdot F}{AK - RK}\left[\frac{B}{R}e^{SR} + \frac{C}{R}e^{VR}\right] \qquad (27)$$

The Raritan River in the tidal sections is characterized by the expanding area function in Equation (25) and by a significant fresh water flow. A material balance around a differential element and integration results in :

BOD :

$$L = BI_r(R) + CK_r(R)$$

DEFICIT :

$$D = GI_a(R) + HK_a(R) + \frac{DK \cdot F}{AK - RK}\left[BI_r(R) + CK_r(R)\right] \qquad (28)$$

Where :

$$I_r = R^V Iv(G_r R)$$

$$K_r = R^V Kv(G_r R)$$

$$I_a = R^V Iv(G_a R)$$

$$K_a = R^V Kv(G_a R)$$

R = Distance from hypothetical origin

$$V = \frac{Q\,Ro}{2E \cdot Ao}$$

$$Gr = (RK/E)^{1/2}$$

$$G_a = (AK/E)^{1/2}$$

$$I_V(GR) = \sum_{K=0}^{\infty} \frac{(GR/2)^{2K-V}}{K!\,\Gamma(K+V+1)}$$

$$K_V(GR) = \frac{\pi}{2} \frac{I_{-V}(GR) - I_V(GR)}{\sin V\pi}$$

Γ = Gamma function

B, C, G, H = Constants

The equations which describe BOD and dissolved oxygen deficit profiles for estuaries with expanding areas are applicable as general equations for each section of the estuary where the area may be considered to expand according to the characteristic formulation. The unknown constants B, C, G, and H, are evaluated by appropriate boundary conditions.

Segmentation of Streams and Estuary Systems

Equations have been developed in the preceding sections for streams and estuaries having constant and variable areas and for constant values of the parameters. Specifically, it was assumed in each of the developments that the parameters AK, RK, DK, E, A, and Q were constant or were defined by a formulation considered in the development of the equation. The solutions thus derived are valid for any length of estuary or stream in which the values of the individual parameters do not change. At the location of changes in the value of individual parameters, it is necessary to segment the system and apply the appropriate general solution to each section.

Additional segments are required for any of the following conditions:

1. Oxidation of nitrogenous compounds may not occur at the point of waste introduction, or may require substantial oxidation of carbon sources and the presence of high dissolved oxygen concentrations. The system is segmented at the point of the beginning of nitrogenous oxidation.

2. The magnitude of the dispersion phenomena may be substantially reduced upstream of the point of maximum salt intrusion.

3. The rate of BOD removal RK may include the effects of settling, stripping, etc., near the location of a raw discharge. In this instance, the rate of BOD removal may be greater than the rate of oxygen utilization, DK. Following the completion of settling or stripping, the rate of BOD removal may be equal to the rate of oxygen utilization. Segmentation is necessary when the rate of BOD removal RK changes value.

4. Fresh water flow may enter a system thus altering the advective velocity and the dilution factor.

5. Segmentation is required at the beginning and end of uniform BOD loads or bottom oxygen demands.

6. Toxic effects may begin or end resulting in changes in the rate of BOD or nitrogenous oxidation. Segmentation is required when changes in rate occur.

7. The cross-sectional area of the body of water may change, thus altering the fresh water velocity and system volume.

8. The depth and/or velocity in an estuary may change, thus altering the value of AK, the reaeration coefficient.

9. Segmentation is required at the confluence of two or more bodies of water.

10. Systems are segmented at the beginning and end of sections where oxygen is produced by algae or rooted aquatic plants.

In addition, estuary and stream systems must be sectioned at the location of all waste inputs which are to be considered. There are two (2) methods available to evaluate the influence of multiple waste inputs. It is possible to construct a model which includes all waste inputs thus requiring system segmentation at each input location.

A second method of evaluating multiple waste loads employs the superposition technique which is valid for the linear equations describing BOD and dissolved oxygen profiles. In the superposition method, the effect of individual waste loads can be evaluated separately. The cumulative effect of loads can be determined by adding the individual BOD and dissolved oxygen deficit profiles.

Evaluation of Boundary Conditions

General equations have been presented describing the BOD and dissolved oxygen deficit profiles in streams and estuary systems. The appropriate equations are applicable to each section of the segmented system. Since the differential equations which were developed in the preceding sections are second degree, their solutions contain two arbitrary constants. The unknown coefficients B and C in the BOD equation and G and H in the deficit equation are evaluated by means of initial or boundary conditions. Evaluations of these conditions also provide a method of linking adjacent system sections which were segmented in accordance with the criteria discussed in the previous section. Since the solution in each segment contains two unknown coefficients, the total number of boundary conditions that must be evaluated in any system is therefore equal to twice the number of segments in the system.

There are three classes of boundary conditions which are appropriate:

1. Infinity conditions - At locations remote from a waste source, the anticipated BOD and dissolved oxygen deficit attributable to the waste source should approach or be equal to zero. This can be stated mathematically by evaluating the BOD or dissolved oxygen deficit equation, at positive or

negative infinity.

2. Concentration equality - At the junction of two segments, the BOD and dissolved oxygen deficit calculated by the equation in either segment must be the same. Thus, the profile equation in the upstream segment must equal the profile equation in the downstream segment at the location of the junction.

3. Mass Balance - It is possible to develop a material balance around an element at the junction of two sections. The quantity of BOD and dissolved oxygen deficit entering the element must equal the quantity of BOD leaving the element.

Proper application of the three general classes of boundary conditions will generate sufficient equations to evaluate all unknown coefficients. In the following pages, examples of evaluation of boundary conditions will be presented for estuary systems. The techniques are identical for fresh water streams when the value of zero is assigned to the dispersion coefficient "E".

In order to illustrate the specific application of boundary conditions, a simplified estuary will be considered with a single waste source located at $x = 0$. The estuary will be considered infinitely long in both directions and having constant cross-sectional area, flow and parameters AK, RK, DK and E.

The estuary must be divided into two segments at the point of waste input. Section one extends upstream from the point of waste input and section two extends downstream from the point of waste discharge. The BOD equations applicable to each section are:

BOD: Section 1 (Upstream)

$$L_1 = B_1 e^{S_1 X} + C_1 e^{V_1 X} \qquad (29)$$

BOD: Section 2 (Downstream)

$$L_2 = B_2 e^{S_2 X} + C_2 e^{V_2 X} \qquad (30)$$

Note that each unknown coefficient and roots S and V are subscripted by section. In like manner the area, flow, reaction and dispersion are subscripted by section. The sectioning procedure results in four (4) unknown coefficients, thus requiring four (4) boundary conditions. The boundary conditions applicable to the example system are:

Boundary Condition	Description and Location
#1	@ $X = -\infty$ $L_1 = 0$
#2	@ $X = +\infty$ $L_2 = 0$
#3	@ $X = 0$ $L_1 = L_2$
#4	@ $X = 0$ mass balance

Boundary Condition #1

At large distances upstream from the waste source, the BOD present in the estuary due to the waste discharges becomes small. Therefore, as X approaches negative infinity ($-\infty$), the BOD in section one approcches zero.

$$L_1 \longrightarrow 0 \text{ as } X \longrightarrow -\infty$$

$$L_1 = 0 \text{ at } X = -\infty$$

$$L_1 = B_1 e^{S_1 X} + C_1 e^{V_1 X}$$

S_1 = positive number

V_1 = negative number

$$e^{+S_1(-\infty)} = \frac{1}{e^{+S_1(+\infty)}} \longrightarrow 0$$

$$e^{-V_1(-\infty)} = e^{V_1 \infty} \longrightarrow \text{large number}$$

If $L_1 = 0$ at $X = -\infty$ C_1 must $= 0$

Equation (29) for section one reduces to:

$$L_1 = B_1 e^{S_1 X}$$

Boundary Condition #2

Using the same reasoning:

$L_2 \longrightarrow 0$ as $X \longrightarrow +\infty$

$L_2 = 0$ at $X = +\infty$

$L_2 = B_2 e^{S_2 X} + C_2 e^{V_2 X}$

$e^{+S_2 (+\infty)} = e^{S_2 \infty} \longrightarrow$ large number

$e^{-V_2 (+\infty)} = \dfrac{1}{e^{(V_2 \infty)}} \longrightarrow 0$

$B_2 = 0$

Equation (30) for section two reduces to:

$L_2 = C_2 e^{V_2 X}$

Boundary Condition #3

At $X = 0$, the BOD concentration calculated by the equation for the BOD profile in section one must equal the concentration as calculated using the BOD profile equation in section two.

$L_1 = L_2$ at $X = 0$

$B_1 e^{S_1 X} = C_2 e^{V_2 X}$

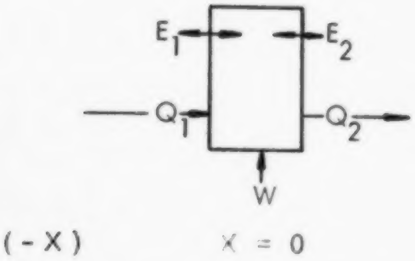
@ $X = 0 \quad e^{S_1 X} = e^{V_2 X} = 1$

and

$$B_1 = C_2 \qquad (31)$$

Boundary Condition #4

Considering a cross-sectional plane at $X = 0$, a flux or material balance can be obtained.



Material entering the section:

$$Q_1L_1 - E_1A_1 \frac{dL}{dX} + W$$

Material leaving the section:

$$Q_2L_2 - E_2A_2 \frac{dL_2}{dX}$$

Balance

$$Q_1L_1 - E_1A_1 \frac{dL_1}{dX} + W = Q_2L_2 - E_2A_2 \frac{dL_2}{dX}$$

or

$$Q_2L_2 - Q_1L_1 = E_1A_1 \frac{dL_1}{dX} - E_2A_2 \frac{dL_2}{dX} + W \qquad (32)$$

Since $Q_2 = Q_1$ and $L_2 = L_1$ at $X = 0$

$$E_1A_1 \frac{dL_1}{dX} - E_2A_2 \frac{dL_2}{dX} = \mathbf{W} \qquad (33)$$

Evaluating $\frac{dL_1}{dX}$ and $\frac{dL_2}{dX}$ at X = 0:

$\frac{dL_1}{dX}$:

$$\frac{dL_1}{dX} = B_1S_1e^{S_1X}$$

$$@\ X = 0;\ \frac{dL_1}{dX} = \underline{\underline{B_1S_1}}$$

$\frac{dL_2}{dX}$:

$$\frac{dL_2}{dX} = C_2V_2e^{V_2X}$$

$$A\ X = 0;\ \frac{dL_2}{dX} = \underline{\underline{C_2V_2}}$$

Substituting into Equation (33)

$$E_1A_1B_1S_1 - E_2A_2C_2V_2 = W$$

Grouping terms:

$$C_2 (- E_2A_2V_2) + B_1 (E_1A_1S_1) = W \qquad (34)$$

Summary of Boundary Equations:

$B_1 - C_2 = 0$ (concentration equality) (31)

$B_1 (E_1A_1S_1) + C_2 (- E_2A_2V_2) = W$ (34)

There are two boundary condition equations and two unknown coefficients remaining, thus it is possible to solve for the unknown coefficients.

$$E_1 = E_2 = E \quad \text{and} \quad A_1 = A_2 = A$$

Combining equations:

$$B_1 (S_1 EA) - B_1 (V_2 EA) = W$$

$$B_1 = \frac{W}{EA\,(S_1 - V_2)}$$

$$C_2 = \frac{W}{EA\,(S_1 - V_2)}$$

and

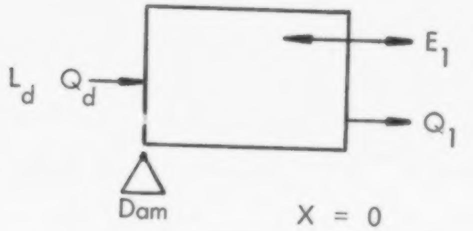
$$L_1 = \frac{W}{EA\,(S_1 - V_2)} e^{S_1 X} \qquad (35)$$

$$L_2 = \frac{W}{EA\,(S_1 - V_2)} e^{V_2 X} \qquad (36)$$

The techniques for evaluating boundary conditions illustrated in the previous example can be employed for evaluating the unknown coefficients in the dissolved oxygen deficit and conservative substance concentration profile equations.

There are three (3) special case boundary conditions which will be illustrated. These are for a system bounded by a dam, a body of water which is completely mixed and an estuary entering a body of water with a fixed concentration.

Mass Balance at a Dam



Material entering the element:

$$Q_d \cdot L_d$$

Material leaving the element:

$$Q_1 \cdot L_1 - E_1 A_1 \frac{dL_1}{dX}$$

Balance: (in = out)

$$Q_d \cdot L_d = Q_1 L_1 - E_1 A_1 \frac{dL_1}{dX} \tag{37}$$

The boundary condition can then be fully evaluated by substituting the appropriate equations for L_1 and $\frac{dL_1}{dX}$ into Equation (37).

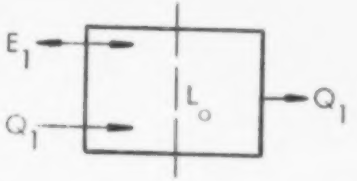
Estuary entering a body having a constant concentration L_o:

Concentration Equation @ $X = XY$

$$L_1 = L_o$$

$$B_1 e^{S_1 XY} + C_1 e^{V_2 XY} = L_o$$

Mass Balance: @ $X = XY$



$X = XY$

Entering section:

$$Q_1 L_1 - E_1 A_1 \frac{dL_1}{dX}$$

Leaving section:

$$L_o Q_1$$

Note: $\frac{dL_o}{dX} = 0$

Since L_o = constant

Balance:

$$Q_1 L_1 - E_1 A_1 \frac{dL_1}{dx} = L_o Q_1 \qquad (38)$$

Substituting the values of L_1 and $\frac{dL_1}{dx}$ into Equation (38) yields the boundary equation.

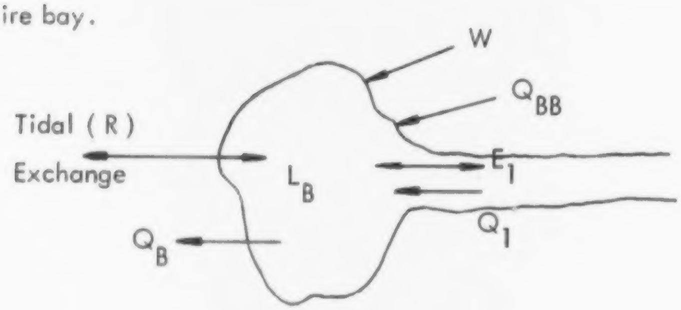
Completely Mixed Bay with Exchange

Concentration Equality:

$$L_1 = L_B$$

Mass Balance:

In this instance, the mass balance is obtained around the entire bay.



Note: $Q_B = Q_1 + Q_{BB}$

Vol = Volume

Entering Bay :

$$Q_1 L_1 - E_1 A_1 \frac{dL_1}{dx} + W$$

Leaving Bay :

$$Q_B L_B + R \cdot L_B + Vol \cdot L_B \cdot RK$$

Balance :

$$Q_1 L_1 - E_1 A_1 \frac{dL_1}{dx} + W = L_B Q_B + Vol \, (R + RK)$$

Evaluating L_1 and $\frac{dL_1}{dx}$ as functions of distance and the unknown coefficients results in the required boundary equation.

An additional concept and phenomena has been introduced in the consideration of the completely mixed bay. The tidal exchange " R " provides a method of evaluating the transport of material out of the bay into the ocean by the tidal volume.

Tidal exchange " R " is defined by :

$$R = \frac{\text{tidal volume}}{\text{mean volume of the bay}}$$

In the simplified estuary problem used as a detailed example of boundary condition evaluation, it was possible to solve for the unknown coefficients B and C manually. As the estuary becomes more complex, it is impractical to evaluate the coefficients manually. In this latter case, it is convenient to arrange the unknown coefficients and boundary condition equations into a matrix and employ computational techniques for numerical evaluation of the unknown coefficients. The boundary condition equation (31) and (34) from our simplified example can be arranged into a matrix:

MATRIX OF UNKNOWN COEFFICIENTS

B.C. No.	B_1	C_2	Forcing Function
3	1	-1	= O
4	EAS_1	$-EAV_2$	= W

The basic method of establishing a matrix of unknown coefficients can be employed regardless of the complexity of the system.

There are several general considerations which are useful in evaluating the unknown coefficients and establishing matrices.

1. Evaluation of boundary conditions always results in a square matrix which means that unique solutions for the values of the unknown coefficients are available.

2. At the junction of " n " segments, there are always generated one mass balance equation and (n - 1) concentration equality equations.
3. The boundary conditions for the BOD and dissolved oxygen solutions are identical. Thus, the matrix of unknown coefficients are identical if the roots of the BOD solution, S and V are replaced by SD and VD, the roots for the deficit solution.
4. The right hand matrix of forcing functions are different for the BOD and dissolved oxygen deficit solution.

METHODS OF ANALYSIS

The preceding sections have presented techniques for developing equations which define the concentration profile of conservative substances, reactive substances, and dissolved oxygen deficit. In addition, a discussion of segmentation and methods of evaluating boundary conditions and unknown coefficients have been presented. It is the purpose of this section to provide guide lines for the method of approach to segmentation and evaluation of the parameters. The following comments will apply to both stream and estuary systems. In the stream systems, the dispersion coefficient " E " is assumed to be zero.

The initial step in developing an analysis of water quality is a critical review of the available information on the body of water under study. Specifically, the following physical, geophysical, and hydrological information must be obtained and evaluated.

1. The mean water depth of the various bodies of water should be determined.

2. The cross-sectional area of the various water bodies should be plotted as a function of location.

3. The drainage area should be evaluated as a function of distance, which provides an insight into fresh water flow quantities. As an example, if a small drainage area is associated with a section of stream or estuary, it is unrealistic to anticipate large fresh water flows from run-off and normal ground water.

4. A qualitative evaluation should be made of the hydrograph of the system. This will assist in determining when field sampling programs might be carried out.

5. If the fresh water flow rate does not significantly change with distance, then the advective velocity of the system can be calculated. On the other hand, if area changes and/or fresh water flow inputs are such that the system advective velocity varies, plots of velocity with distance should be developed.

6. Knowing the tidal velocity in estuaries and the flow velocity in streams a plot of " AK ", the reaeration coefficient vs. distance, using equation (42) to calculate " AK ", is constructed.
7. The confluence of major water bodies should be noted on the distance plots.
8. The BOD removal and oxidation coefficients RK and DK should be evaluated from appropriate information.
9. The dispersion coefficient in estuaries should be assigned, or evaluated.
10. Waste sources should be located and indications of the magnitude of loads obtained.
11. Chloride or other conservative substance profiles should be constructed. BOD and dissolved oxygen deficit profiles as a function of distance should be developed from any existing data.

It is usually advisable as a first step to construct a model incorporating as many simplifying assumptions as practical.

Having assessed the reliability of the available information on the physical, hydrodynamic and input data, the various distance plots are compared in an attempt to minimize the number of segments required. Changes in area and flow may be assumed to occur at the confluence of two bodies of water, thus reducing the number of segments required. Adjacent waste inputs can be combined at their center of gravity to reduce the number of segments. All of these steps are contingent upon the availability of data and the degree of complexity of the model justified by the available information.

It is possible to evaluate the various parameters, U, E, RK, DK, R, and Ak from physical, hydrodynamic and observed data.

Advective Velocity (U)

The flow velocity which transports material out of the estuary can be evaluated:

$$U = \frac{Q}{A} \qquad (39)$$

Dispersion (E)

A plot of the log of the concentration of a conservative substance (usually chlorides) vs. distance results in a straight line. The slope of the line is equal to:

$$\text{Slope} = U/E$$

therefore;

$$E = U/\text{slope} \qquad (40)$$

BOD Removal and/or Deoxygenation (RK and/or DK)

A plot of the log of the BOD vs. distance results in a straight line. The slope of the line is defined by:

$$\text{Slope} = \frac{U}{2E} \left[1 \pm \left(1 + \frac{4 \cdot RK \cdot E}{U^2} \right)^{1/2} \right] \qquad (41)$$

The value of RK can be obtained from the solution of the above equation.

If the rate of BOD removal changes, the semi-log plot of BOD vs. distance will yield two (2) straight lines having different slopes. The slope of the line adjacent to the waste input will provide a measure of RK. The slope of the line farthest from the waste input is generally employed to calculate DK. The calculated value of DK must be equal to or less than RK. This analysis for calculating the values of RK and DK is valid only for BOD data which results from a single waste input. If the BOD profile is influenced by several waste inputs which can not be grouped into a single source of BOD, the above analysis is not valid. A reasonable first assumption for the range of values of RK and DK is 0.20 - 0.50 to the base, " e ", with the two parameters assumed to be equal.

Reaeration Coefficient

This parameter can be calculated as follows:

$$AK = \frac{D \cdot U^{1/2}}{H^{3/2}} \qquad (42)$$

D = diffusivity in Equation (42)

The velocity is the average velocity over a tidal cycle in estuaries and the advective velocity in streams.

Temperature Effects

Temperature influences the parameters AK, RK, and DK. Generally accepted temperature corrections for these parameters are:

$$AK_{(T)} = AK_{(20^\circ C)} 1.02^{(t-20)}$$

$$RK_{(T)} = RK_{(20^\circ C)} 1.04^{(t-20)}$$

$$DK_{(T)} = DK_{(20^\circ C)} 1.04^{(t-20)}$$

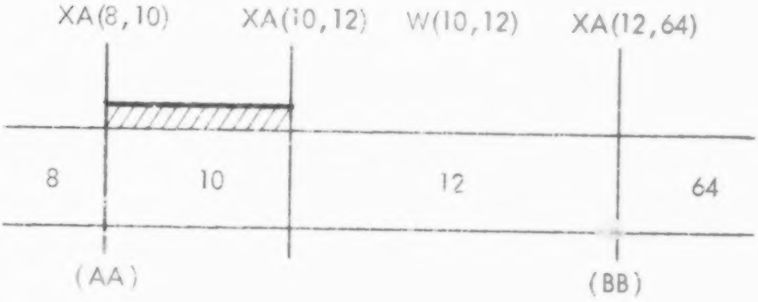
$$RK_{N(T)} = RK_{N(20^\circ C)} 1.08^{(t-20)}$$

In addition, temperature will also significantly influence the saturation value of dissolved oxygen which in turn will change the dissolved oxygen deficit. Tables are available indicating temperature and dissolved solids effects on the saturation value of oxygen in water.

METHOD FOR EVALUATION AND PRESENTATION OF BOUNDARY CONDITIONS FOR COMPLEX ESTUARIES

In all sections provision can be made for the input of a point load, a uniform load, bottom sediment oxygen demand, and algae. To provide maximum flexibility, the following loading procedures can be employed:

LOADING PROCEDURE EXAMPLE



Sectioning points AA and BB are assumed required by parameter o area changes. A load W(10,12) at a variable distance XA(10,12) is located between sections 10 and 12 as shown. The equation for the BOD and dissolved oxygen deficit in sections 10 and 12 contains provision for uniform load input, bottom deposits, and algae. If it is desired to load the system with a point load W(10,12) at location XA(10,12), then the remaining inputs are made equal to zero. That is, WU(10), WU(12), BD(10), BD(12), P(10), P(12), R(10) and R(12), are all zero. If, on the other hand, a uniform load is the only input to be employed from Section 8 to point XA(10,12) then W(10, 12) becomes zero. All other inputs are also zero, with the exception of WU(10) which has a value. The length of the uniform load may be changed by increasing the value of XA(10, 12) to approach the limit XA(12, 64) or decreasing the value of XA(10, 12) to approach XA(8, 10) as a limit. This procedure can be repeated for other inputs or for uniform waste loads in section 12.

The spherical coordinate system does not allow for ready introduction of uniform loads. Where these coordinate systems are employed WU must be zero.

Some additional points on loadings and boundary conditions should be noted with regard to the expanding area sections. When expanding areas are involved in a boundary condition, the value of area at the location of the boundary must be calculated and employed in the mass balance boundary evaluations. In addition, the value of area used in uniform load introduction for expanding area segments employing cylindrical coordinates is the average cross-sectional area over the length of the uniform waste input.

The matrix of unknown coefficients generated for complex water quality models can become large. Presentation of the specific values of the elements of the matrix for BOD and deficit solutions would be obscure. In view of the above, and the fact the complex systems must be evaluated on a computer, the following procedure can be adopted for presentation of the water quality models.

1. The BOD and dissolved oxygen deficit equations can be presented in general form.
2. The various segments can be assigned alternate numbers, (i.e., 2, 4, 6, and 8) in recognition that each segment generates two unknown coefficients. Exceptions, which are completely mixed volumes or sections bounded by infinity conditions, must be specifically indicated.
3. A table can be developed defining the specific functional forms of the general equations for the BOD and dissolved oxygen deficit solutions as determined by the area-distance relationships encountered.
4. The concentration boundary condition may be generalized in four (4) classes which cover all of the concentration

equality equations encountered in the present system. The four classes of concentration equality boundary equations can be presented in a form which is amenable to matrix solution.

5. The first derivative of the generalized BOD and dissolved oxygen deficit concentration profile equations can be defined in tabular form.
6. Eight (8) generalized solutions to the mass balance boundary condition equations can be presented. These equations cover all of the mass balance conditions required in the present systems. The mass balance equations have been presented in a form amenable to matrix solution of the simultaneous equations developed.
7. The boundary conditions may be classified and tabulated.
8. The specific boundary conditions from the general classification listing can be presented in tabular form for each junction.

The appropriate designation of upstream and downstream must also be indicated.

9. A model can then be constructed by joining segments.

The formulas describing water quality in any specific segment (I) can be written in the general form:

$$L(I) = B(I)f_r(X,I) + C(I)\bar{f}_r(X,I) + YB(I) \qquad (43)$$

$$D(I) = G(I)f_a(X,I) + H(I)\bar{f}_a(X,I) + YD(X,I) \qquad (44)$$

Where:

(I) = Section number

(X,I) = Indicates that the expressions are a function of both section and location " X " in the section.

L(I) = BOD in Section I.

D(I) = Dissolved oxygen deficit in Section I.

B(I) and C(I) = Unknown coefficients for the BOD equation.

$G(I)$ and $H(I)$ = Unknown coefficients for the deficit equations.

$f_r(X,I)$ and $\overline{f}_r(X,I)$ = Functional forms for the BOD equation. The specific forms are defined in Table 4.

$YB(I)$ = Particular integral for the BOD solution as defined in Table 4.

$YD(X,I)$ = Particular integral for the deficit solution as defined in Table

$f_r(X,I)$, $\overline{f}_r(X,I)$, $f_a(X,I)$, and $\overline{f}_a(X,I)$ are functions of distances X or R and segment number "I". $YB(I)$ is a function only of the segment number "I" and $YD(X,I)$ is a function of segment and location. The specific functions vary, depending upon the geometry of the segment under consideration. Table 4 presents the form of the functions for the area variations with distance encountered in the subject waterways.

There are three (3) possible special cases which do not have the form indicated above. They are:

1. Negative infinity boundary conditions where the only unknown coefficient is the B or G coefficient.

TABLE 4

FUNCTIONAL VALUES FOR SEVERAL AREA VS. DISTANCE RELATIONSHIPS

FUNCTIONS	AREA RELATIONSHIPS Constant Area	 $A = Ao\left(\frac{R}{Ro}\right)$	 $A = Ao\left(\frac{R}{Ro}\right)^2$
$f_r(X, I)$	$e^{S(I)X}$	$I_{r_{(I)}}(R)$	$\frac{e^{S(I)R}}{R}$
$\overline{f}_r(X, I)$	$e^{V(I)X}$	$K_{r_{(I)}}(R)$	$\frac{e^{V(I)R}}{R}$
$f_a(X, I)$	$e^{SD(I)X}$	$I_{a_{(I)}}(R)$	$\frac{e^{SD(I)R}}{R}$
$\overline{f}_a(X, I)$	$e^{VD(I)X}$	$K_{a_{(I)}}(R)$	$\frac{e^{VD(I)R}}{R}$
YB(I)	$\frac{WU(I)}{A(I) \cdot RK(I)}$	$\frac{WU(I)}{AA(I) \cdot RK(I)}$	zero
YD(X, I)	$\frac{BD(I)}{HT(I) \cdot AK(I)} + \frac{R(I)-P(I)}{AK(I)}$ $+ \frac{DK(I) \cdot WU(I) \cdot F(I)}{AK(I) \cdot RK(I) \cdot A(I)}$ $\frac{DK(I) \cdot F(I)}{AK(I)-RK(I)}\ [\ B(I) f_r(X, I)$ $+ C(I)\overline{f}_r(X, I)\ ]$	$\frac{BD(I)}{HT(I) \cdot AK(I)} + \frac{R(I)-P(I)}{AK(I)}$ $+ \frac{DK(I) \cdot WU(I) \cdot F(I)}{AK(I) \cdot RK(I) \cdot AA(I)}$ $\frac{DK(I) \cdot F(I)}{AK(I)-RK(I)}\ [\ B(I) f_r(X, I)$ $+ C(I)\overline{f}_r(X, I)\ ]$	$\frac{BD(I)}{HT(I) \cdot AK(I)}$ $+ \frac{R(I) - P(I)}{AK(I)}$ $+ \frac{DK(I) \cdot F(I)}{AK(I)-RK(I)}$ $\cdot\ [\ B(I) f_r(X, I) + C(I)\overline{f}_r(X, I)\ ]$

$$L(I) = B(I)f_r(X, I) + YB(I) \tag{45a}$$

$$D(I) = G(I)f_a(X, I) + YD(I) \tag{45b}$$

2. Positive infinity boundary conditions where the only unknown coefficient is the C or H coefficient.

$$L(I) = C(I)\bar{f}_r(X, I) + YB(I) \tag{46a}$$

$$D(I) = H(I)\bar{f}_a(X, I) + YB(I) \tag{46b}$$

3. Completely mixed volumes.

$$L(I) = B(I) \tag{47a}$$

$$D(I) = G(I) \tag{47b}$$

For completely mixed volumes the BOD and deficit does not vary with distance and can therefore be defined by constants $B(I)$ and $G(I)$ respectively.

At the junction point of adjacent segments there are $(n - 1)$ concentration equality equations and one mass balance equation. It is possible to generalize the concentration equality boundary equation number, referred to as "J" for any two adjacent segments, "I" and "K" to indicate the elements of the matrix of unknown coefficients, " AM " and the elements of the forcing function matrices, " BFORC " for the BOD, and " DFORC " for the deficit.

BOD Concentration Equality Equation :

$$B(I)f_r(X, I)+C(I)\bar{f}_r(X, I)-B(K)f_r(X, K)-C(K)\bar{f}_r(X, K) = YB(K)-YB(I) \qquad (48)$$

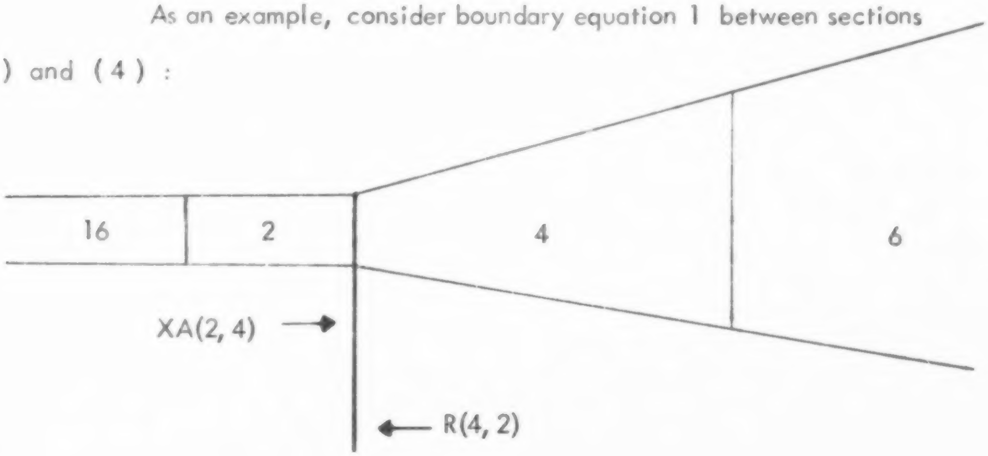
Equation (48) is presented such that all terms which include the unknown coefficients "B" and "C" are on the left hand side and all terms that can be completely evaluated compose the right hand member. The left hand member of Equation (48) is presented in matrix AM below:

Boundary Condition	B(I)	C(I)	B(K)	C(K)
(J)	$f_r(X, I)$	$f_r(X, I)$	$-f_r(X, K)$	$-f_r(X, K)$

NOTE: "J" is the equation number and row number of the AM matrix.

The functions $f_r(X, I)$ and $\bar{f}_r(X, I)$, $f_r(X, K)$ and $\bar{f}_r(X, K)$ are evaluated for sections "I" and "K" respectively at the appropriate value of X or R for each segment.

As an example, consider boundary equation 1 between sections (2) and (4) :



EQUATION FOR CONCENTRATION EQUALITY

$J = 1$

Evaluating functions:

Section I:

$I = 2$

$X = XA(2,4)$

$$\left.\begin{aligned} fr(X,I) &= e^{S(2)} \cdot XA(2,4) \\ \bar{fr}(X,I) &= e^{V(2)} \cdot XA(2,4) \end{aligned}\right\} \quad \text{From Table 4}$$

Section K:

$K = 4$

$X = R(4,2)$

$$\left.\begin{aligned} fr(X,I) &= Ir(4(R(4,2))) \\ fr(X,I) &= Kr(4(R(4,2))) \end{aligned}\right\} \quad \text{From Table 4}$$

Arranging the left member of the equation in matrix form yields:

MATRIX AM

Boundary Condition #	B(2)	C(2)	B(4)	C(4)
1	$e^{S(2)} \cdot XA(2,4)$	$e^{V(2)}XA(2,4)$	$-Ir(4(R(4,2)))$	$-Kr(4(R(4,2)))$

The right-hand side of the concentration equation are the forcing functions :

$$\mathrm{BFORC(J)} = \mathrm{YB(4)} - \mathrm{YB(2)} \tag{49}$$

$$\mathrm{DFORC(J)} = \mathrm{YD(4)} - \mathrm{YD(2)} \tag{50}$$

Note that the signs for the forcing functions for any segment, (I or K) are the reverse of the sign of the elements in the AM matrix.

Presenting this boundary condition in a general form, which can be readily employed to generate a matrix :

Class 1 Boundary Condition - (Concentration Equality)

Elements of AM Matrix for Sections
I and K and Boundary Condition J

B(I)	$\mathrm{AM(I-1, J)} = f_r(X, I)$
C(I)	$\mathrm{AM(I, J)} = \bar{f}_r(X, I)$
B(K)	$\mathrm{AM(K-1, J)} = -f_r(X, K)$
C(K)	$\mathrm{AM(K, J)} = -\bar{f}_r(X, K)$

$$\mathrm{BFORC(J)} = \mathrm{YB(K)} - \mathrm{YB(I)}$$

$$\mathrm{DFORC(J)} = \mathrm{YD(X, K)} - \mathrm{YD(X, I)}$$

For deficit Matrix AM, replace f_r and $\bar{f}_r$ by f_a and $\bar{f}_a$, respectively.

Class 2 Boundary Condition (Concentration Equality, Negative Infinity Boundary for Section I, with C(I)=0)

Same as Class 1 Boundary Condition, with

C(I)	AM(I,J) = 0

Forcing functions are the same as for Class 1 Boundary Condition.

Class 3 Boundary Condition (Concentration Equality, Positive Infinity Boundary for Section K, with B(K)=0)

Same as Class 1 Boundary Condition, with

B(K)	AM(K-1,J) = 0

Class 4 Boundary Condition (Concentration Equality, in a Completely Mixed Volume)

B(I)	AM(I-1,J) = $f_r(X,I)$
C(I)	AM(I,J) = $\bar{f}_r(X,I)$
B(KK)	AM(KK,J) = -1

BFORC(J) = -YB(I)

DFORC(J) = -YD(X,I)

Additional classes of boundary conditions are required for the mass balances. Before evaluation of mass balance boundary conditions, it is necessary to define the first derivatives of the concentration profile equations:

$$\frac{dL}{dx}(I) = B(I)f_r'(X,I) + C(I)\bar{f}_r'(X,I) + YB'(I)$$

$$\frac{dD}{dx}(I) = G(I)f_a'(X,I) + H(I)\bar{f}_a'(X,I) + YD'(X,I)$$

Table presents the definitions of the functions f_r', $\bar{f}_r'$, f_a', $\bar{f}_a'$, YB', and YD' for the several area-distance relationships used in the present models.

Generalized solutions are available for the mass balances when sections I, K, and KK are considered and the boundary equation number is defined by J. It must be noted that Section I is defined as upstream, or more negative than SectionK. (That is, flow from Section I enters Section K.) The direction of Section KK must be indicated.

Class 5 Boundary Condition (Mass Balance,
Two Adjacent Sections)

B(I)	$AM(I-1,J) = E(I)\cdot A(I)\cdot f_r'(X,I) - Q(I)f_r(X,I)$
C(I)	$AM(I,J) = E(I)\cdot A(I)\cdot \bar{f}_r'(X,I) - Q(I)\bar{f}_r(X,I)$
B(K)	$AM(K-1,J) = Q(K)f_r(X,K) - E(K)\cdot A(K)\cdot f_r'(X,K)$
C(K)	$AM(K,J) = Q(K)\bar{f}_r(X,K) - E(K)\cdot A(K)\cdot \bar{f}_r'(X,K)$

BFORC(J) = W(n) (load entering at junction) + $Q(I)YB(I) - Q(K)YB(K)$

$$DFORC(J) = Q(I)YD(X,I) - E(I)\cdot A(I)\cdot YD'(X,I) + E(K)\cdot A(K)\cdot YD'(X,K) - Q(K)YD(X,K)$$

TABLE 5

DERIVATIVES OF FUNCTIONAL VALUES FOR SEVERAL AREA-DISTANCE RELATIONSHIPS

	AREA RELATIONSHIPS		
Function	Constant Area	$A = Ao \left(\frac{R}{Ro}\right)$	$A = Ao \left(\frac{R}{Ro}\right)^2$
$f'_r(X,I)$	$S(I)e^{S(I)X}$	$I'_r(I)(R)$	$\left(S(I) - \frac{1}{R}\right)\frac{e^{S(I)R}}{R}$
$\bar{F}'_r(X,I)$	$V(I)e^{V(I)X}$	$K'_r(I)(R)$	$\left(V(I) - \frac{1}{R}\right)\frac{e^{V(I)R}}{R}$
$f_a(X,I)$	$SD(I)e^{SD(I)X}$	$I'_a(I)(R)$	$\left(SD(I) - \frac{1}{R}\right)\frac{e^{SD(I)R}}{R}$
$\bar{f}'_a(X,I)$	$VD(I)e^{VD(I)X}$	$K'_a(I)(R)$	$\left(VD(I) - \frac{1}{R}\right)\frac{e^{VD(I)R}}{R}$
$YB'(I)$	zero	zero	zero
$YD'(X,I)$	$\frac{DK(I) \cdot F(I)}{AK(I)-RK(I)} \left[B(I) f'_r(X,I) + C(I) \bar{f}'_r(X,I) \right] \longrightarrow$		

Class 6 Boundary Condition (Mass Balance with Negative Infinity Boundary for Section I makes C(I) = 0)

Same as Class 5 boundary condition with

$C(I) \;\Big|\; AM(I, J) = 0$

Class 7 Boundary Condition (Mass Balance with Positive Infinity Boundary for Section K makes B(K) = 0

Same as for Class 5 boundary condition with

$B(K) \;\Big|\; AM(K-1, J) = 0$

Class 8 Boundary Condition (Mass Balance with Flow Entering Sections K and KK from Section I)

AM(I-1, J), AM(I, J), AM(K-1, J)

and AM(K, J), are the same as for

Class 5 Boundary Condition

$B(KK) \;\Big|\; AM(KK-1, J) = Q(KK)f_r(X, KK)-E(KK)\cdot A(KK)\cdot f_r'(X, KK)$

$C(KK) \;\Big|\; AM(KK, J) = Q(KK)\overline{F}_r(X, KK)-E(KK)\cdot A(KK)\cdot \overline{F}_r'(X, KK)$

$BFORC(J) = W(N)+Q(I)YB(I)-Q(K)YB(K)-Q(KK)YB(KK)$

DFORC(J) = DFORC(J) in class 5 boundary, plus:

$E(KK)\cdot A(KK)\cdot YD'(X, KK)-Q(KK)YD(X, KK)$

Class 9 Boundary Condition (Mass Balance with flow Entering Section K from Sections I and KK)

AM(I-1, J) , AM(I, J) , AM(K-1, J) and AM(K, J) are the same as for Class 5 boundary condition.

$$\begin{array}{l|l} B(KK) & AM(KK-1, J) = E(KK)\cdot A(KK)\cdot f_r'(X, KK) - Q(KK)\cdot f_r(X, KK) \\ C(KK) & AM(KK, J) = E(KK)\cdot A(KK)\cdot \mathcal{F}_r'(X, KK) - Q(KK)\cdot \mathcal{F}_r(X, KK) \end{array}$$

$$BFORC(J) = W(N)+Q(I)YB(I)+Q(KK)YB(KK)-Q(K)YB(K)$$

DFORC(J) = DFORC(J) as in Class 5 boundary condition, plus :

$$Q(KK)\cdot YD(X, KK) - E(KK)\cdot A(KK)\cdot YD'(X, KK)$$

Class 10 Boundary Condition (Mass Balance at Section With Advective Flux, Only)

$$\begin{array}{|l} AM(K-1, J) = Q(K)\cdot f_r(X, K) - E(K)\cdot A(K)\cdot f_r'(X, K) \\ AM(K, J) = Q(K)\cdot \mathcal{F}_r(X, K) - E(K)\cdot A(K)\cdot \mathcal{F}_r'(X, K) \end{array}$$

$$BFORC(J) = L(DAM) - Q(K)YB(K)$$

$$DFORC(J) = E(K)\cdot A(K)\cdot YD'(X, K) - Q(K)\cdot YD(X, K) + DEF(DAM)$$

L(DAM) and DEF(DAM) equal the concentration of BOD and dissolved oxygen deficit in the flow over a dam at the base of the dam.

Class 11 Boundary Condition (Mass Balance with Section I Leaving Completely Mixed Volume, KK)

$$AM(i-1,J) = Q(I)\cdot f_r(X,I) - E(I)\cdot A(I)\cdot f_r'(X,I)$$

$$AM(I,J) = Q(I)\cdot \bar{f}_r(X,I) - E(I)\cdot A(I)\cdot \bar{f}_r'(X,I)$$

$$AM(KK,J) = VOL(KK)\cdot RK(KK)$$

$$BFORC(J) = W\ (\text{bay load}) - Q(I)YB(I)$$

$$DFORC(J) = E(I)\cdot A(I)\cdot YD'(X,I) - Q(I)\cdot YD(X,I) + F(KK)\cdot DK(KK)B(KK)$$

For two Sections I and K leaving a completely mixed volume, add AM(K-1,J) and AM(K,J) which are identical in form to AM(I-1,J) and AM(I,J). To the forcing functions, add:

$$BFORC(J)\ \text{plus}\ - Q(K)\cdot YB(I)$$

$$DFORC(J)\ \text{plus}\ E(K)\cdot A(K)\cdot YD'(X,K) - Q(I)YD(X,K)$$

Class 12 Boundary Condition (Mass Balance, Section I Entering a Completely Mixed Volume, KK, with a tidal Exchange and Flow from the Volume to the Infinite Medium)

$$AM(I-1,J) = E(I)\cdot A(I)f_r'(X,I) - Q(I)f_r(X,I)$$

$$AM(I,J) = E(I)\cdot A(I)\bar{f}_r'(X,I) - Q(I)\bar{f}_r(X,I)$$

$$AM(KK,J) = (Q(KK) + R(KK)VOL(KK))+VOL(KK)\cdot RK(KK))$$

$$BFORC(J) = W(KK) + Q(I)YB(I)$$

$$DFORC(J) = Q(I)YD(X,I) - E(I)\cdot A(I)\cdot YD'(X,I) + F(KK)\cdot AK(KK)B(KK)$$

For two sections, I and K, entering a completely mixed volume, add AM(K-1, J) and AM(K, J), which are identical in form to AM(I-1, J) and AM(I, J) : to the forcing functions, add:

BFORC(J) plus +Q(K)YB(K)
DFORC(J) plus Q(K)YD(X, K)-E(K)A(K)YD(X, K)

Table 6 presents a summary of the instances of application for the various boundary condition classifications. If boundary classifications 2 and 6 are used, the section equation is given by Equation (45) and if boundary classifications 3 and 7 are used, Equation (46) is applicable. Equation (47) is used for boundary conditions 11 and 12. The proper equations are employed in the boundary classifications. These comments are offered to assist in using the proper equation to calculate intermediate concentration values.

The boundary condition classifications applicable to each section are described in Table 6.

The elements for the matrix of unknown coefficients for the dissolved oxygen deficit are generated by replacing the functions $f_r(X, I)$ and $\bar{f}_r(X, I)$ by $f_a(X, I)$ and $\bar{f}_a(X, I)$, respectively. The parameter RK is replaced by the parameter AK in the mass balance boundary conditions for completely mixed volumes.

TABLE 6

APPLICATION FOR BOUNDARY CLASSIFICATIONS

Boundary Classification	Types of Applications
1	Concentration equality when both sections have two (2) unknown coefficients and are bounded at both ends.
2	Concentration equality when one section has two (2) unknown coefficients and the second section has only B or G coefficient, (negative infinity).
3	As number two, with second section having a C or H coefficient, (positive infinity).
4	Concentration equality in a completely mixed volume.
5	Mass balance between two sections, both sections having two (2) unknown coefficients.
6	Mass balance when one section has two (2) unknown coefficients and the second section has only B or G coefficients (negative infinity).
7	Same as six, with second section having a C or H coefficient. (positive infinity).
8	Mass balance for three (3) sections with flow from one section dividing into the two sections.
9	Mass balance for three (3) sections with flow from two sections combining into the third section.
10	Mass balance at a section of advective flux only (dam).
11	Mass balance at a section with completely mixed volume. Flow leaves the bay through the section.
12	Mass balance at completely mixed volume when flow enters bay through the section.

The subscripted area term A(I) in the mass balance boundary condition is the cross-sectional area for segments having constant cross-sectional area. The cross-sectional area at location (XA(K,I)) must be used for segments having variable cross-sectional areas. The particular integral in the BOD solution for uniform loads contains an area term. For segments having a variable cross-sectional area, the average area over the length of the uniform load is to be employed as the area term, AA(I).

Example Using Boundary Classifications :

In order to facilitate use of the general boundary classifications the estuary system illustrated in Figure 1 will be considered as an example. Table 7 presents the functional forms for the various sections, and Table 8 indicates the general boundary classifications applicable to each specific section and junction.

From Table 4 it is determined that the equations for the various sections are :

$$L(2) = B(2) \qquad (51)$$

$$L(4) = B(4)I_r(4)(R) + C(4)K_r(4)(R) + YB(4) \qquad (52)$$

$$L(6) = B(6)e^{S(6)X} + YB(6) \qquad (53)$$

Table 4 was employed to define the functional forms of sections 4 and 6 as Bessel functions and exponential functions, respectively. The specific forms of YB are also shown in this table.

It is observed that there are four (4) unknown coefficients and that evaluation of the boundary conditions yields four (4) boundary equations. The matrix formed is illustrated in Table 9.

The deficit matrix is formed by replacing f_r, $\bar{f}_r$, and RK by f_a, $\bar{f}_a$, and AK. The right-hand matrix DFORC(J) is formed, using the standard boundary conditions and Tables 4 and 5.

From the above example, it may be observed that section sub -

EXAMPLE FOR APPLYING THE GENERAL BOUNDARY CONDITIONS

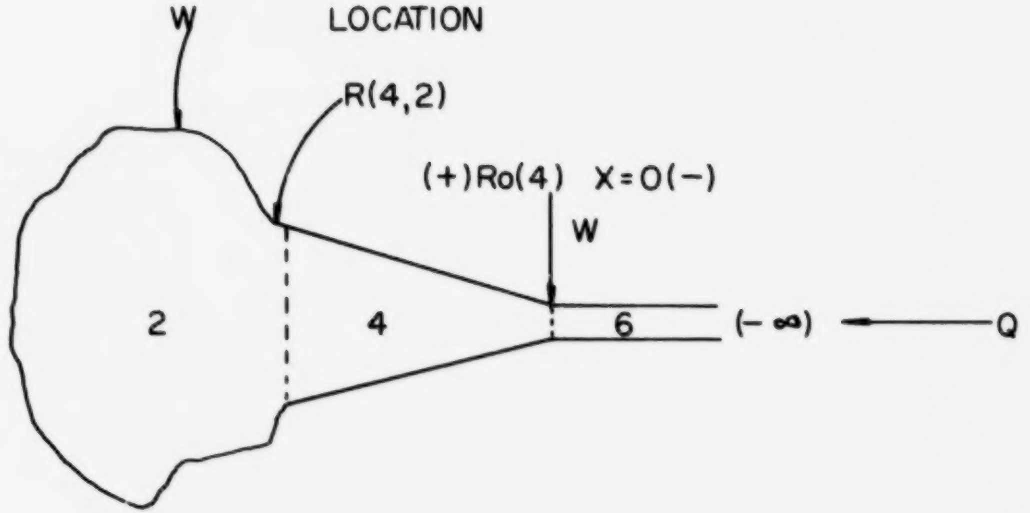

W
LOCATION
R(4,2)
(+)Ro(4) X=0(-)
W
2
4
6
(- ∞)
Q

FIGURE I

TABLE 7

FUNCTIONAL FORMS IN EXAMPLE ESTUARY

(Sections illustrated on Figure 1)

Constant Area:

Section 6 (Use Equation 45)

Variable Area $A = Ao \frac{R}{Ro}$:

Section 4

Mixed Volume :

Section 2 (Use Equation 47)

TABLE 8

BOUNDARY CLASSIFICATIONS - EXAMPLE ESTUARY

(Sections illustrated on Figure 1)

Boundary Classification	I	K	KK	J(Boundary Number)
2 - 6 (See Table 6)	6	4	--	2
4 - 12 (See Table 6)	4	2	--	4

TABLE 9

MATRIX FOR EXAMPLE PROBLEM

	B(2)	B(4)	C(4)	B(6)	Coefficients
Equation No.	1	2	3	4	
1	0	X	X	X	Concentration Equality Classification No. 2
2	0	X	X	X	Mass Balance Classification No. 6
3	X	X	X	0	Concentration Equality Classification No. 4
4	X	X	X	0	Mass Balance Classification No. 12

NOTE: "X" signifies non-zero elements of the matrix defined by the element of the general boundary classifications.

scripting has a profound influence on the complexity of the computer program which is required to solve the matrix and calculate the BOD and dissolved oxygen profiles. This example has employed an arbitrary section subscripting system. It is strongly suggested that before final section subscripts are assigned, the individual who is going to write the computer program be consulted. Subscripting of sections to facilitate programming is beyond the scope of the present study.

Having established the right and left-hand matrices for the BOD and dissolved oxygen deficit solutions, it is possible to solve for the values of the unknown coefficients and water quality profiles can then be calculated in each section.

STUDY AREA - COMPONENT WATERWAYS AND SEGMENTATION

The basic study area shown in Figure 2 can be subdivided into five major systems. These major systems are:

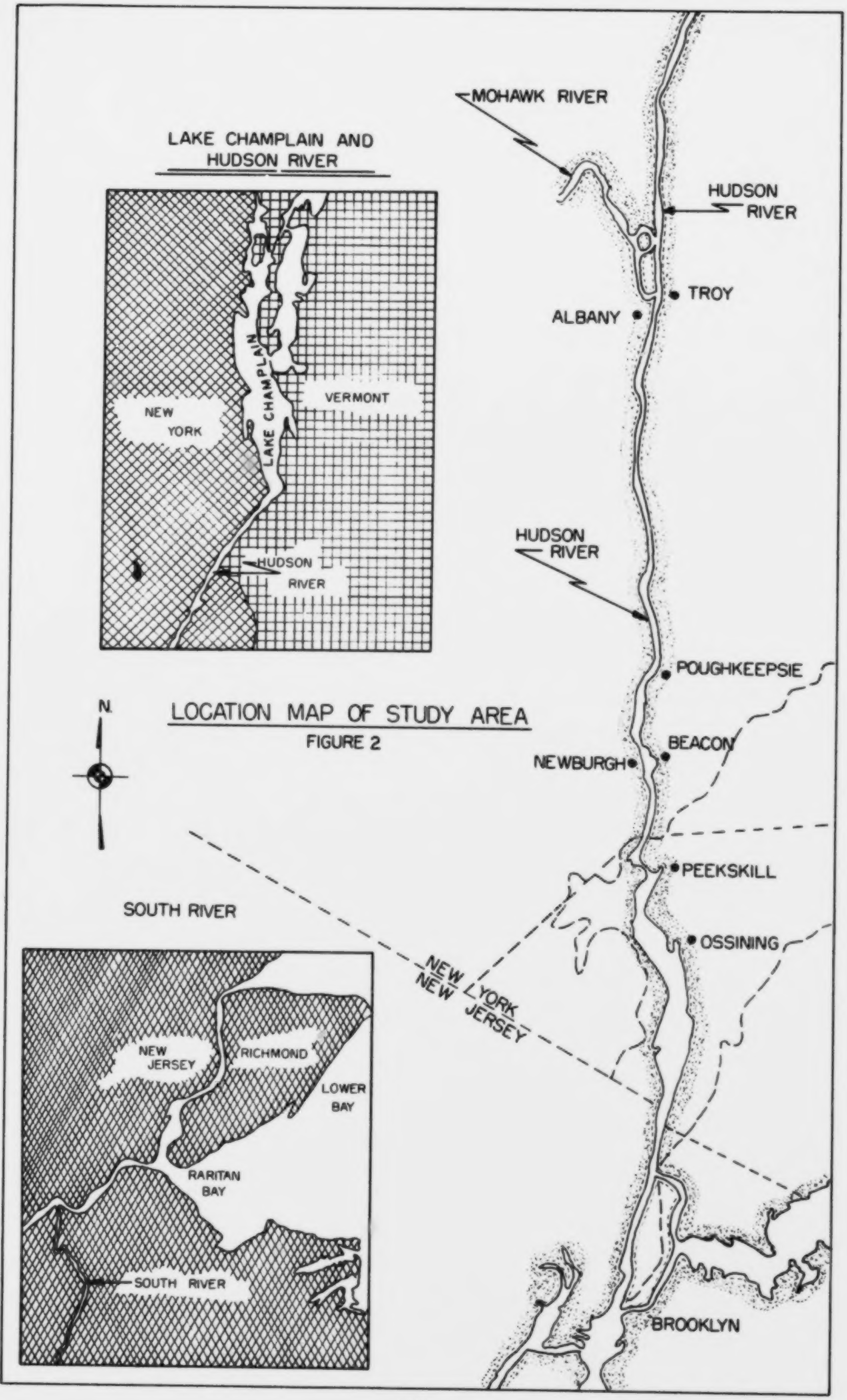
1. New York Harbor Complex
2. Hudson River Estuary in the Albany Troy area
3. Middle Hudson River (between Hudson River Estuary and New York Harbor)
4. Tidal section of the Raritan River
5. Lake Champlain

Each major system can subsequently be segmented or subdivided into components which can be evaluated based on the amount and quantity of information available.

New York Harbor Complex

Figure 3 is a sketch of the New York Harbor Complex. This system of waterways was further subdivided in the following manner:

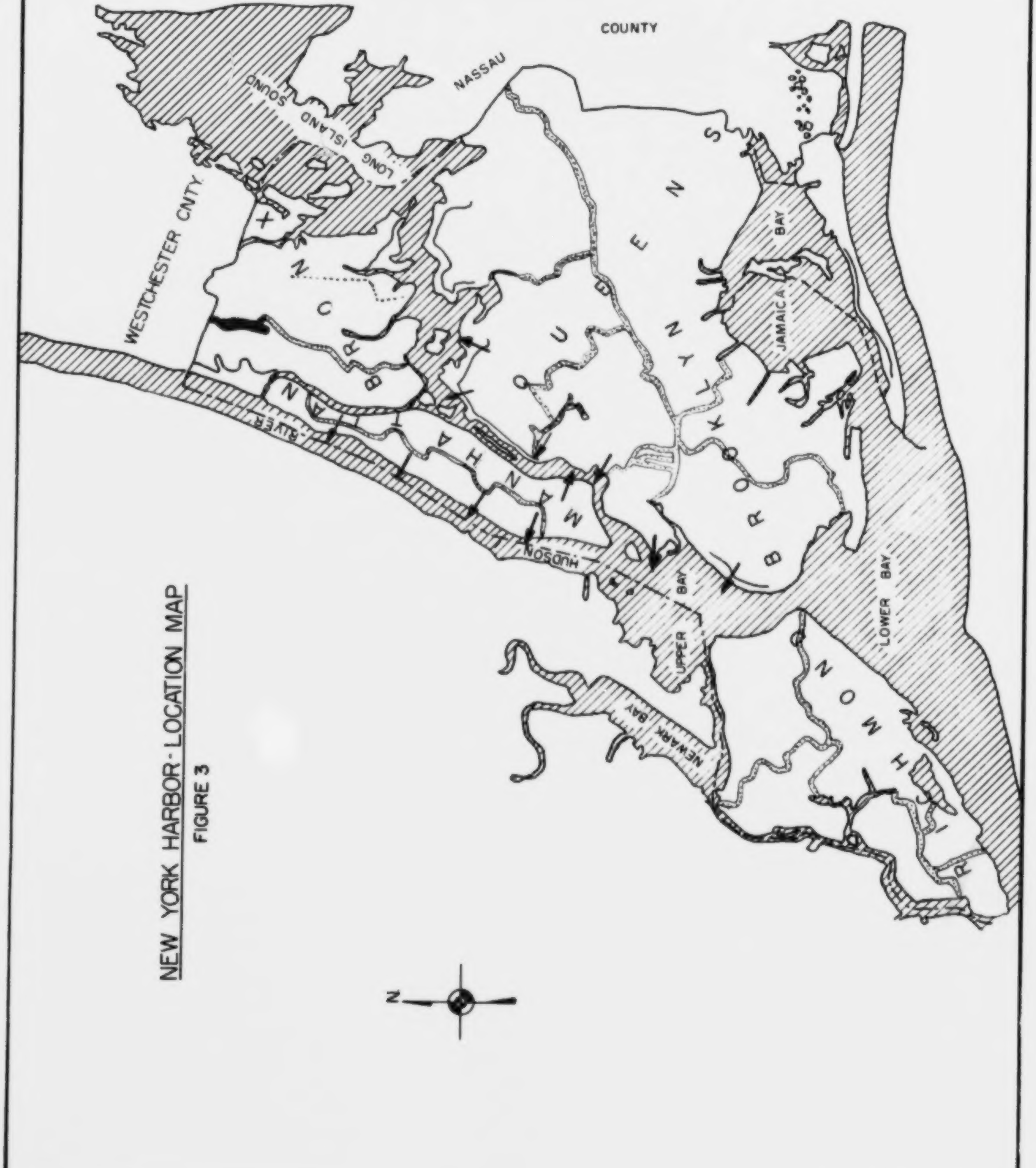
1. East River System
2. North River System
3. Arthur Kill System



LOCATION MAP OF STUDY AREA

FIGURE 2

LAKE CHAMPLAIN AND HUDSON RIVER
NEW YORK
LAKE CHAMPLAIN
VERMONT
HUDSON RIVER
N.
SOUTH RIVER
NEW JERSEY
RICHMOND
LOWER BAY
RARITAN BAY
SOUTH RIVER
MOHAWK RIVER
HUDSON RIVER
TROY
ALBANY
HUDSON RIVER
POUGHKEEPSIE
BEACON
NEWBURGH
PEEKSKILL
OSSINING
NEW YORK
NEW JERSEY
BROOKLYN


WESTCHESTER CNTY.
LONG ISLAND SOUND
NASSAU COUNTY
BRONX
QUEENS
BROOKLYN
MANHATTAN
RICHMOND
HUDSON RIVER
UPPER BAY
LOWER BAY
JAMAICA BAY
NEWARK BAY
N

NEW YORK HARBOR - LOCATION MAP
FIGURE 3

East River System

The East River System which consists of the lower East River bounded by the upper New York Harbor and the upper East River is schematically shown on Figure 4.

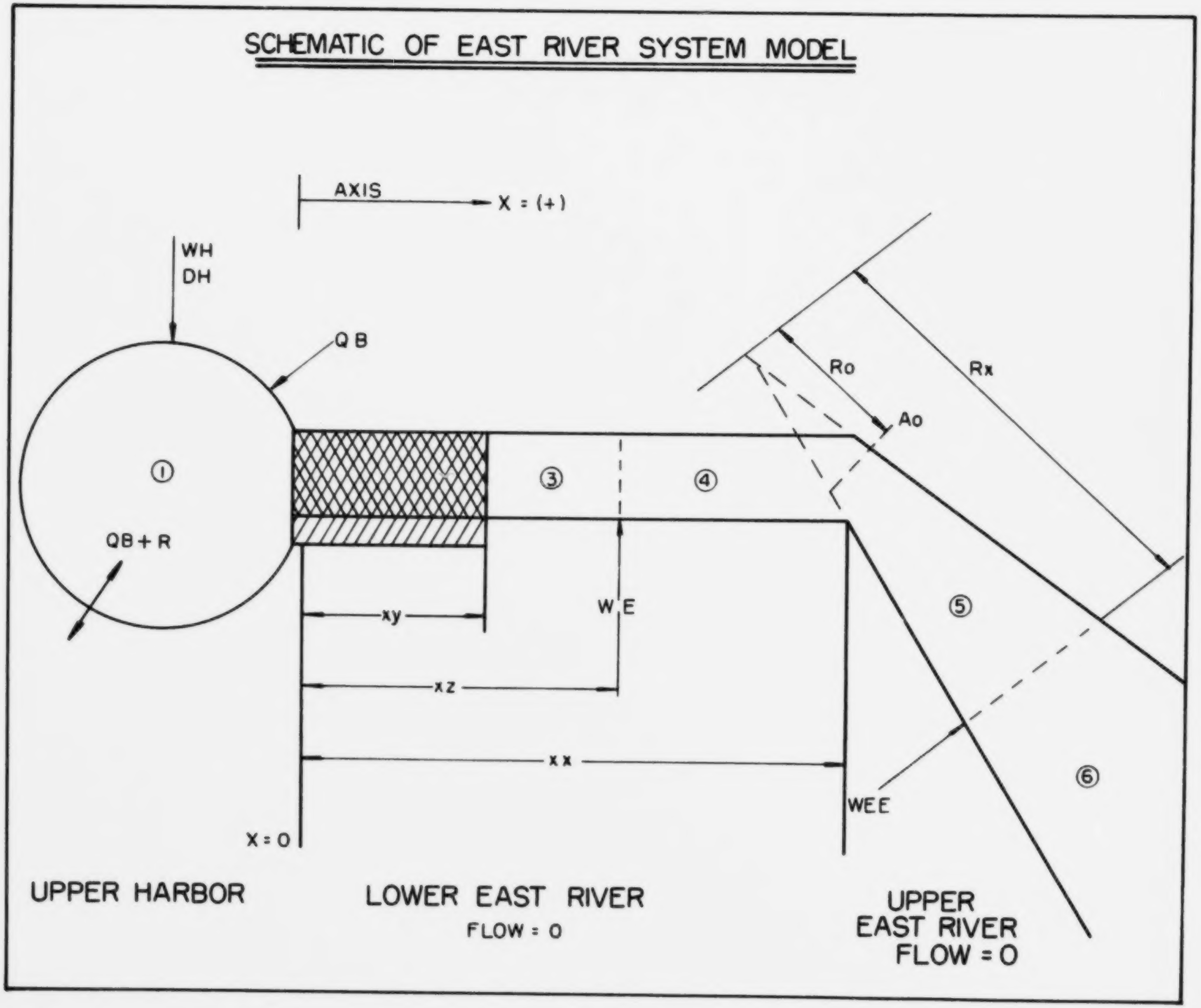
Basic assumptions made were that the harbor is a completely mixed body and that the advective flow in the upper and lower East River is zero. Figures 5 and 6 are plots of the area and AK as a function of distance. The area of the lower East River was considered to be constant, and equal to 80,000/ft^2, while the area of the upper East River varied as a function of distance as shown in Equation 54:

$$A = A_o \left(\frac{R}{R_o} \right)^2 \qquad (54)$$

$$A_o = 80,000$$

$$R_o = 15.2 \text{ miles}$$

The East River system was initially subdivided into three models with a load in each component waterway for the manual development of water quality equations. A computer program for calculation of the dissolved oxygen deficit and BOD profiles in the East River system was developed at the New York University computer center.



SCHEMATIC OF EAST RIVER SYSTEM MODEL

AXIS
X = (+)
WH
DH
QB
①
QB + R
③
④
Ro
Rx
Ao
⑤
⑥
xy
W E
xz
xx
WEE
X = 0
UPPER HARBOR
LOWER EAST RIVER
FLOW = 0
UPPER
EAST RIVER
FLOW = 0

FIGURE 4

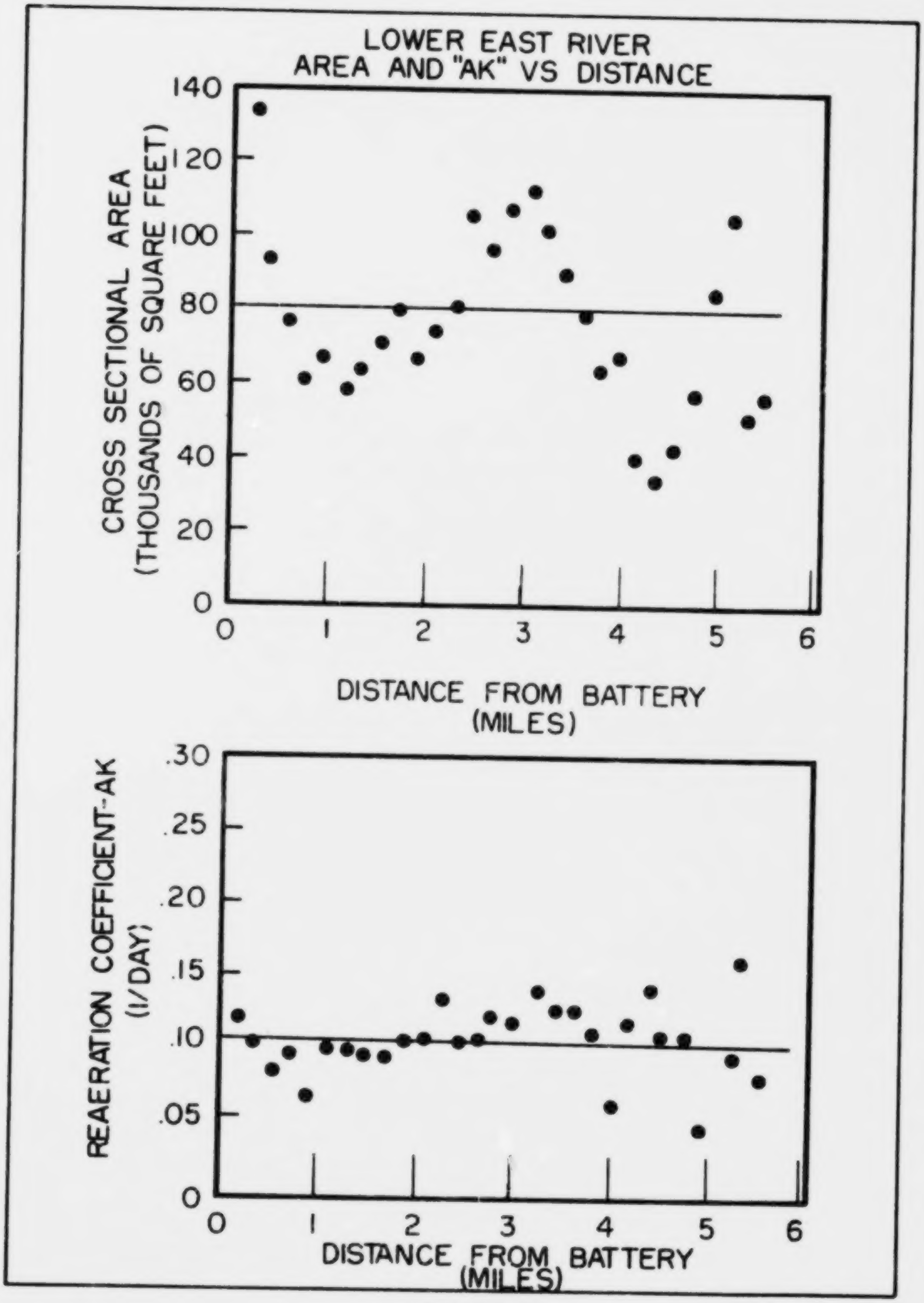

LOWER EAST RIVER
AREA AND "AK" VS DISTANCE
CROSS SECTIONAL AREA
(THOUSANDS OF SQUARE FEET)
0
20
40
60
80
100
120
140
0
1
2
3
4
5
6
DISTANCE FROM BATTERY
(MILES)
REAERATION COEFFICIENT-AK
(1/DAY)
0
.05
.10
.15
.20
.25
.30
0
1
2
3
4
5
6
DISTANCE FROM BATTERY
(MILES)

FIGURE 5

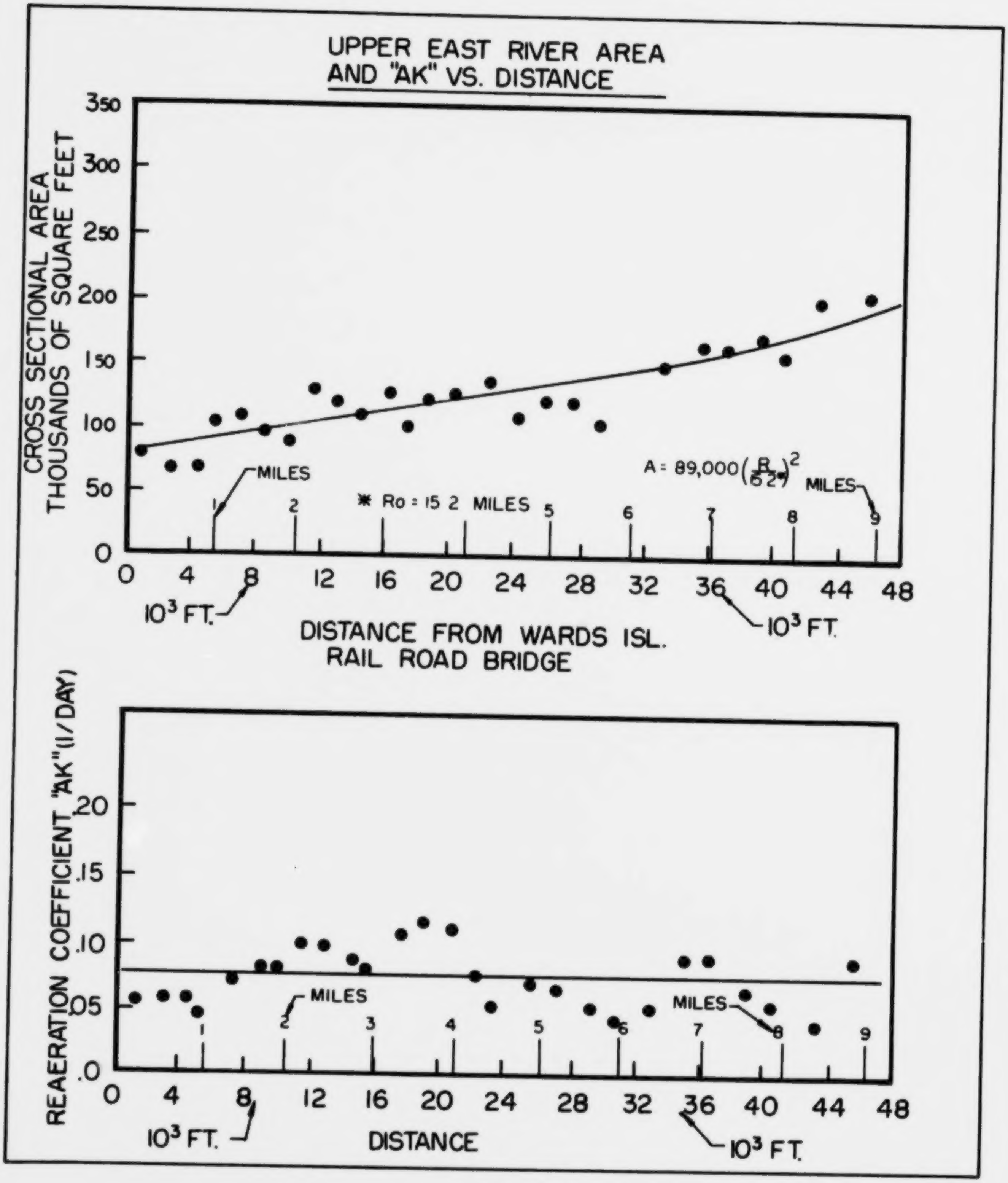

UPPER EAST RIVER AREA
AND "AK" VS. DISTANCE
CROSS SECTIONAL AREA
THOUSANDS OF SQUARE FEET
350
300
250
200
150
100
50
0
MILES
1
2
* Ro = 15 2 MILES
5
6
7
8
9
A = 89,000 (R/52*)²
MILES
0
4
8
12
16
20
24
28
32
36
40
44
48
10³ FT.
10³ FT.
DISTANCE FROM WARDS ISL.
RAIL ROAD BRIDGE
REAERATION COEFFICIENT "AK" (1/DAY)
.20
.15
.10
.05
.0
MILES
1
2
3
4
5
6
7
8
9
MILES
0
4
8
12
16
20
24
28
32
36
40
44
48
10³ FT.
DISTANCE
10³ FT.

FIGURE 6

North River System

The North River system is schematically shown on Figure 7 and consists of the East River, upper New York Harbor, and the Hudson River. Figures 8 and 9 present the area and reaeration coefficient, AK, as a function of distance for upper New York Harbor and the Hudson River in the vicinity of New York City. Figure 10 presents the comparable data for the Harlem River. The North River model is constructed considering the Hudson River to be a flowing body. This concept of a flowing body applies to the upper Harbor, which in the North River model is not considered a completely mixed bay. The East River segment of the model is for a constant cross-sectional area as a function of distance.

Manual evaluation of the mathematical water quality models required three models with a load in each section. The computer program defining the North River system has been developed at New York University.

Arthur Kill System

a) Lower Arthur Kill
b) Upper Arthur Kill
c) Newark Bay

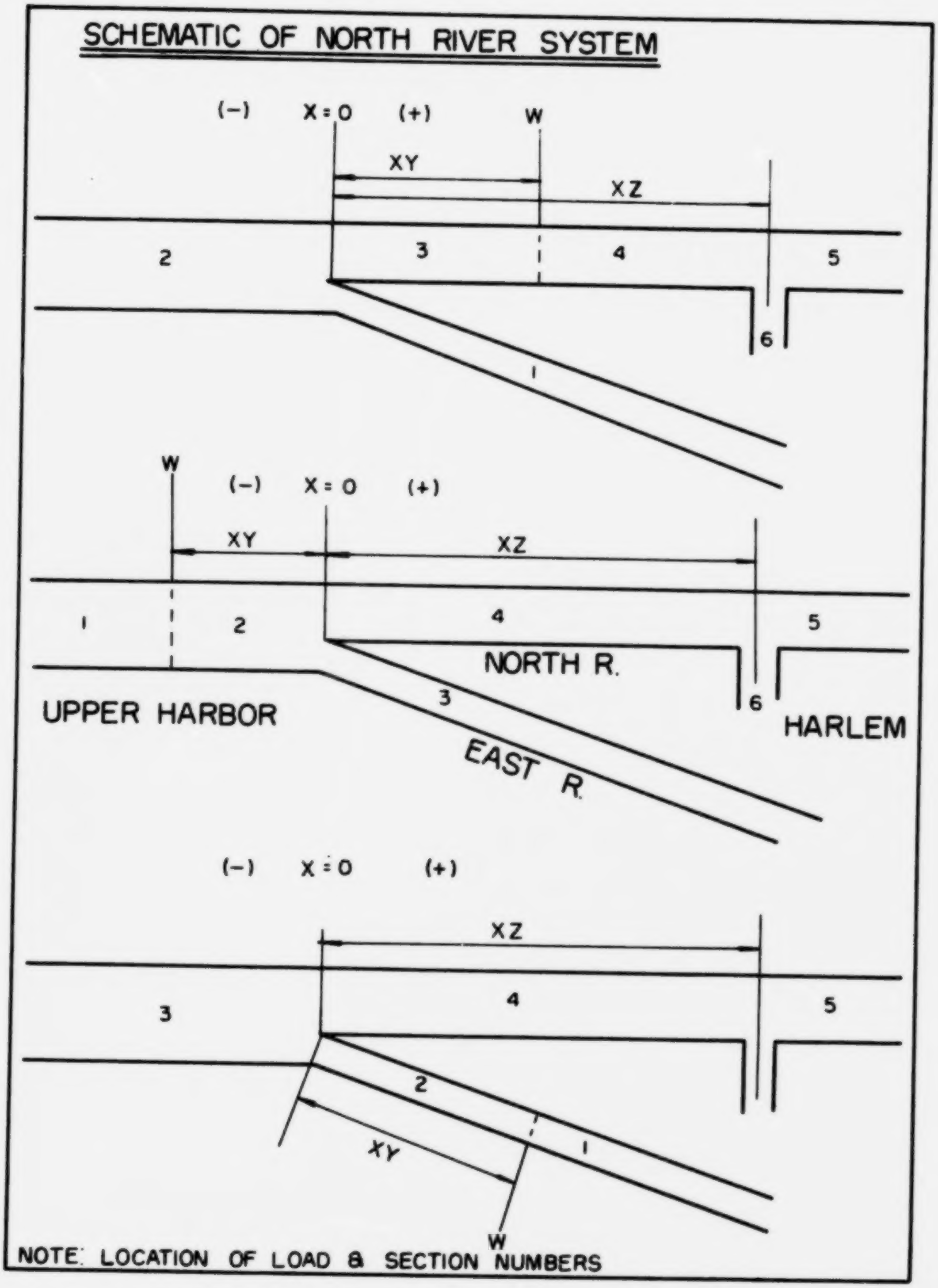

SCHEMATIC OF NORTH RIVER SYSTEM
(−)
X = 0
(+)
W
XY
XZ
2
3
4
5
6
1
W
(−)
X = 0
(+)
XY
XZ
1
2
4
5
NORTH R.
3
6
UPPER HARBOR
HARLEM
EAST R.
(−)
X = 0
(+)
XZ
3
4
5
2
1
XY
W
NOTE: LOCATION OF LOAD & SECTION NUMBERS

FIGURE 7

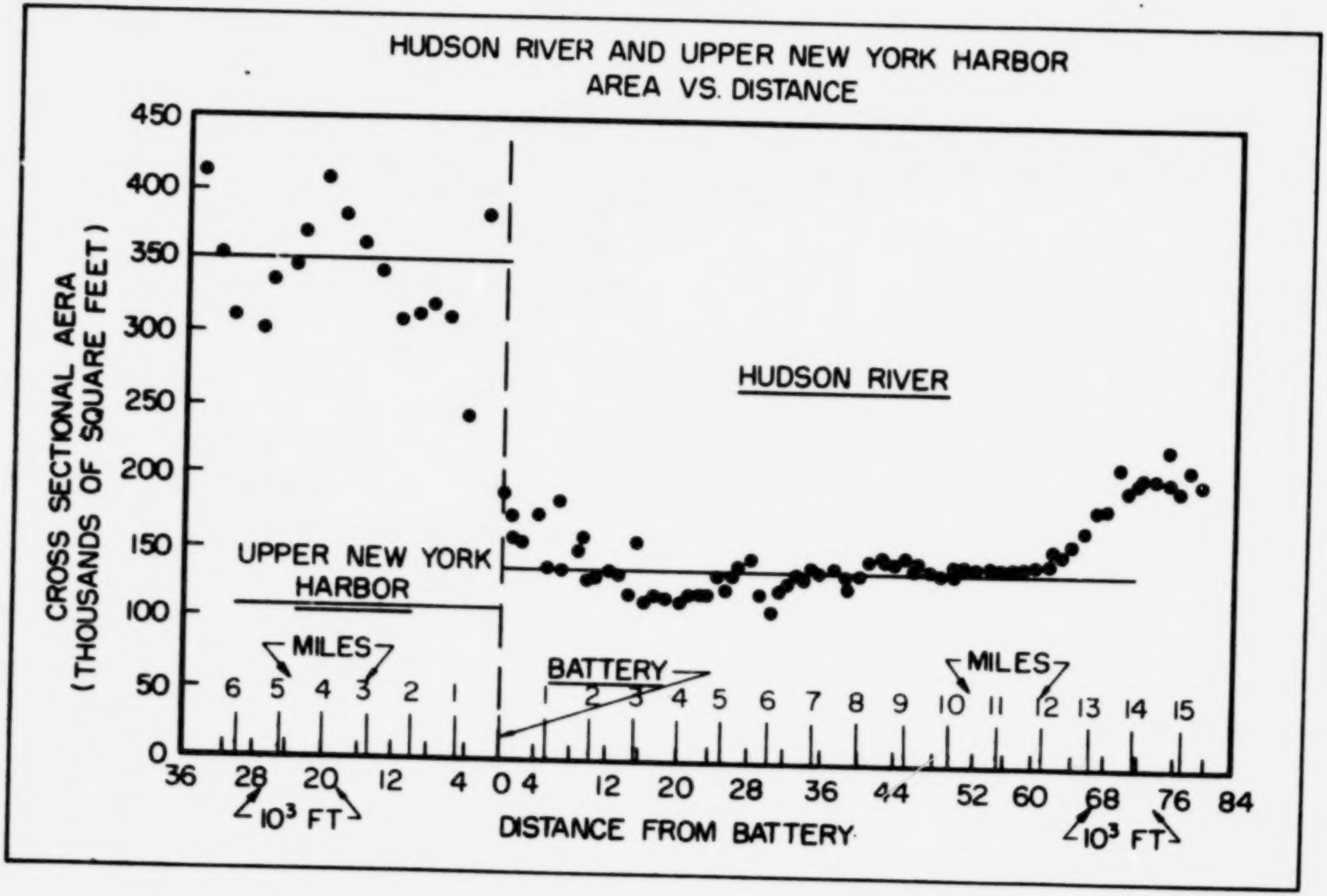
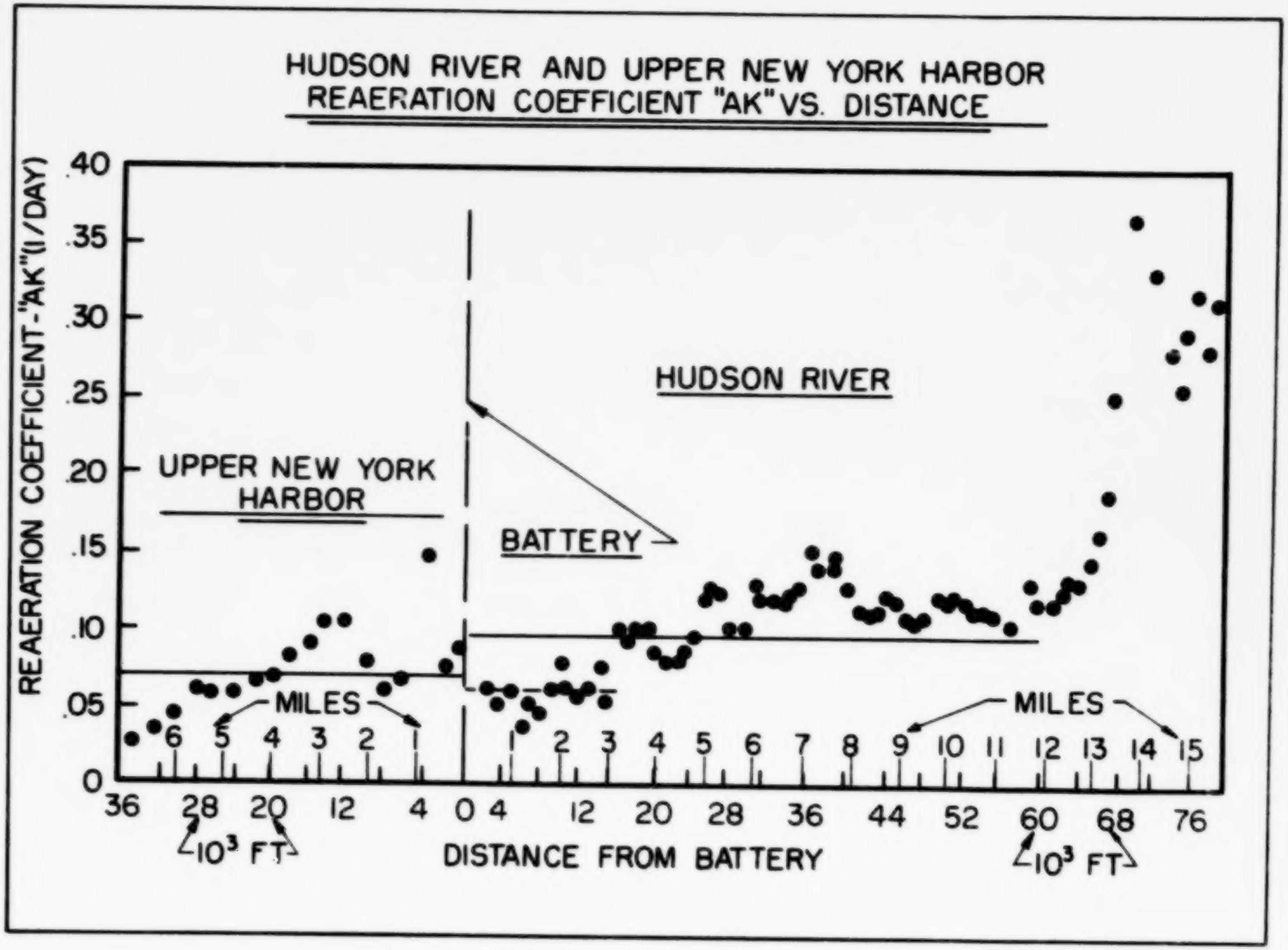

HUDSON RIVER AND UPPER NEW YORK HARBOR
AREA VS. DISTANCE
CROSS SECTIONAL AERA
(THOUSANDS OF SQUARE FEET)
450
400
350
300
250
200
150
100
50
0
UPPER NEW YORK
HARBOR
HUDSON RIVER
MILES
6
5
4
3
2
1
BATTERY
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
MILES
36
28
20
12
4
0
4
12
20
28
36
44
52
60
68
76
84
10³ FT
10³ FT
DISTANCE FROM BATTERY

FIGURE 8



HUDSON RIVER AND UPPER NEW YORK HARBOR REAERATION COEFFICIENT "AK" VS. DISTANCE

FIGURE 9

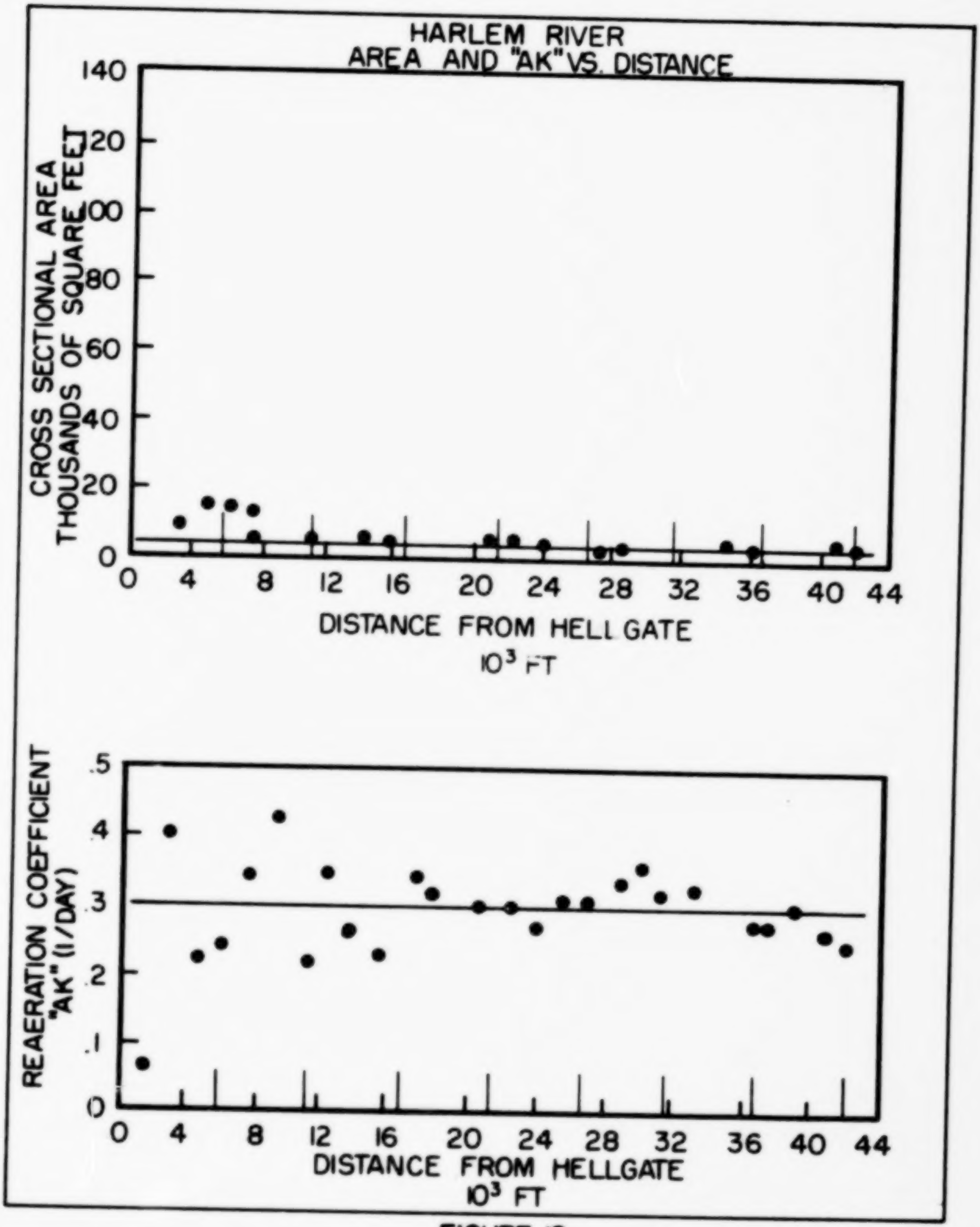

HARLEM RIVER
AREA AND "AK" VS. DISTANCE
CROSS SECTIONAL AREA
THOUSANDS OF SQUARE FEET
140
120
100
80
60
40
20
0
0
4
8
12
16
20
24
28
32
36
40
44
DISTANCE FROM HELL GATE
10³ FT
REAERATION COEFFICIENT
"AK" (1/DAY)
.5
.4
.3
.2
.1
0
0
4
8
12
16
20
24
28
32
36
40
44
DISTANCE FROM HELLGATE
10³ FT

FIGURE 10

Figure 11 presents area vs distance for the system. An analysis of the Arthur Kill system indicates that the mathematical model is identical in form to the East River system. The models presented for the East River system are therefore directly applicable to the Arthur Kill system. The basic physical alterations in the models is in the length of the constant area section of the model which for the Arthur Kill system is 1.0 miles, as compared to 9.2 miles in the East River system. The expanding area portion of the Arthur Kill is characterized by the area function:

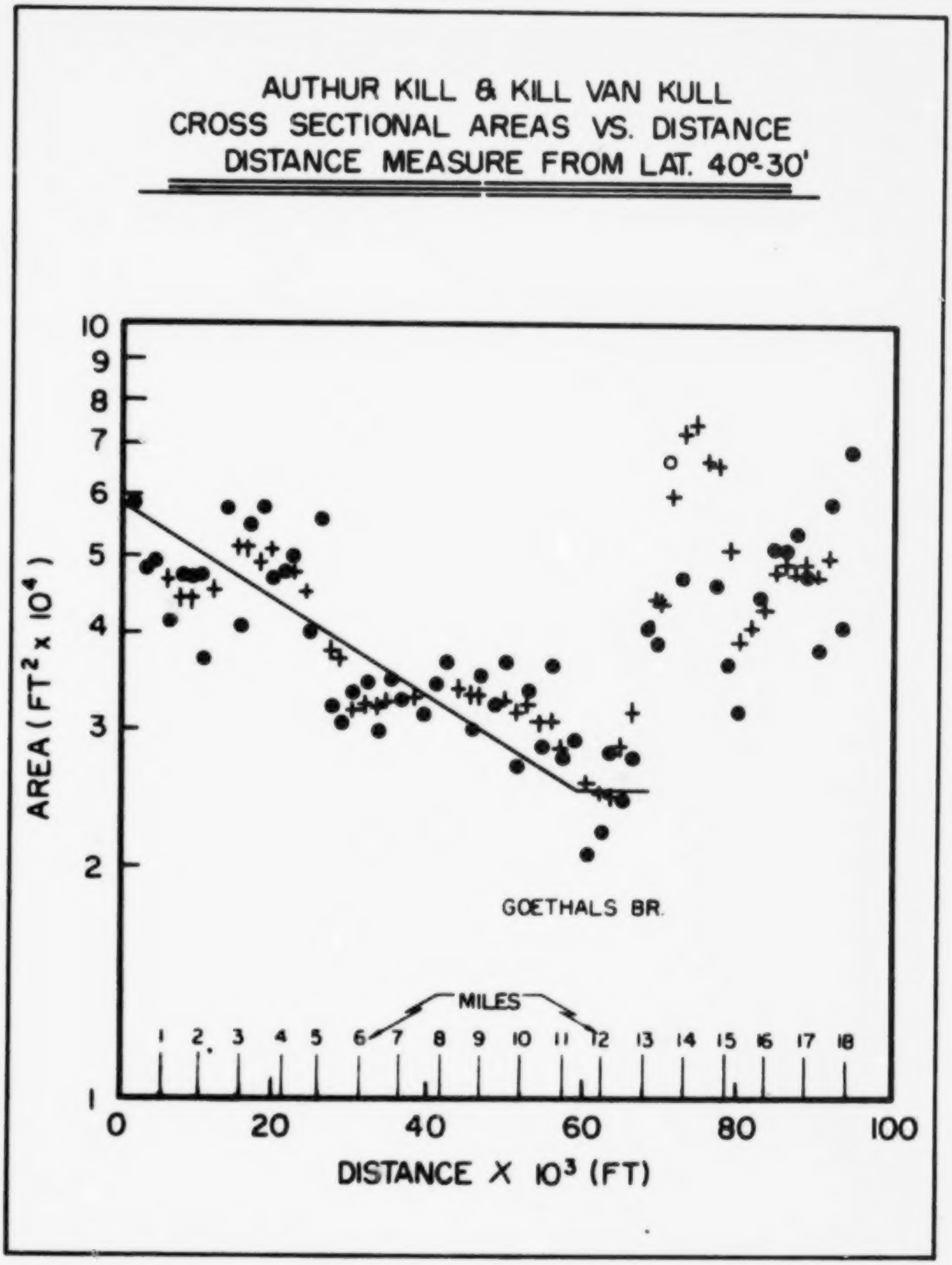
$$A = A_o \left(\frac{R}{R_o} \right)^2$$

where:

$$R_o = 26 \text{ miles}$$

$$A_o = 24,250 \text{ ft}^2$$

In a similar manner, fresh water flow into the Arthur Kill system would come from the Passaic and Hackensack Rivers into Newark Bay. Flow and tidal exchange is assumed to exist between Newark Bay and upper New York Harbor.



AUTHUR KILL & KILL VAN KULL
CROSS SECTIONAL AREAS VS. DISTANCE
DISTANCE MEASURE FROM LAT. 40°-30'

FIGURE 11

Raritan River Tidal Section

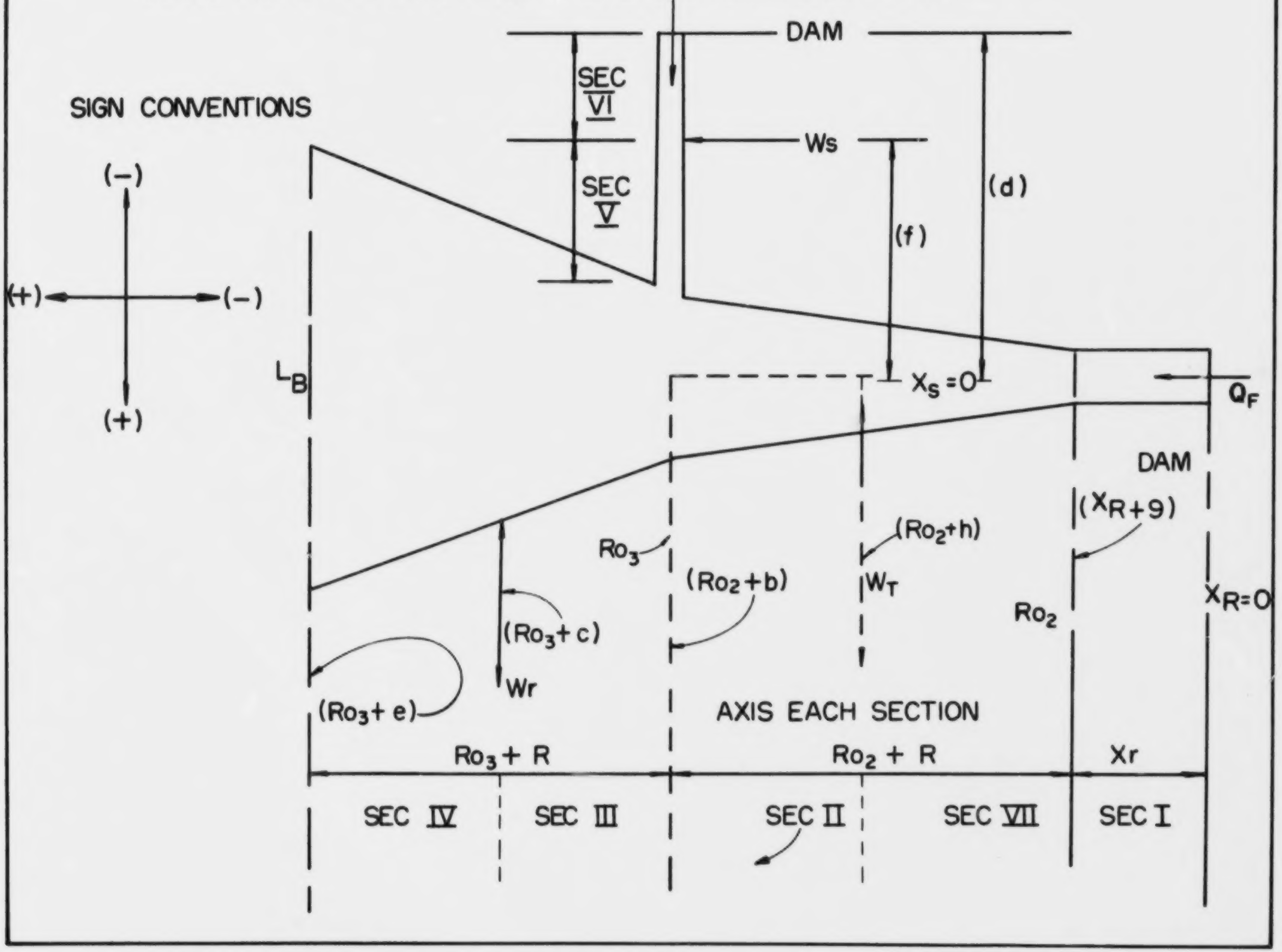
The Raritan River tidal section model incorporates the Raritan River from the Fieldville Dam to Raritan Bay, and includes the South River to the Duhernal Dam. Figure 12 is a schematic representation of the Raritan River model. The system is characterized by two (2) points of flow introduction over dams and BOD and dissolved oxygen deficit concentrations in Raritan Bay which are influenced by loads that are external to the Raritan River model. It is therefore necessary to assign constant concentration values to three locations. The BOD and dissolved oxygen deficit entering the system over the Fieldville and Duhernal Dams must be assigned as inputs. The BOD and dissolved oxygen deficit in Raritan Bay must also be assigned a numerical value.

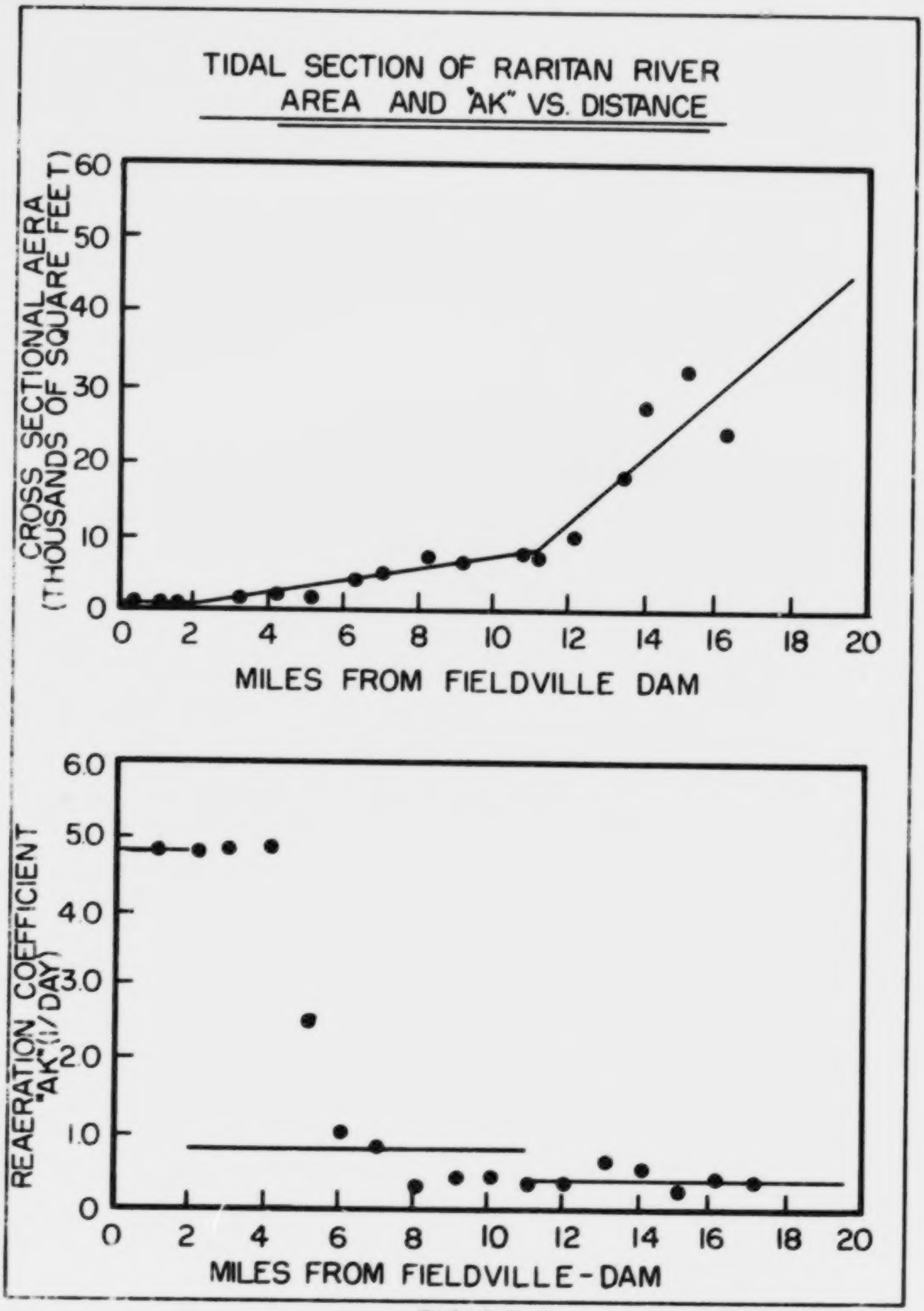
The Raritan River in the tidal section has been characterized by an expanding area having the form: (See Figure 13)

$$A = A_o \frac{R}{R_o}$$

A Bessel function solution to the BOD and dissolved oxygen deficit profile equations results. Table 10 presents a list of the boundary conditions employed to develop the model. Table 11 presents a list

SCHEMATIC OF RARITAN RIVER TIDAL SECTION MODEL FIGURE


SIGN CONVENTIONS
(−)
(+)
(−)
(+)
DAM
SEC VI
SEC V
Ws
(d)
(f)
$X_S = 0$
Q_F
L_B
DAM
(X_{R+9})
(Ro_2+h)
W_T
Ro_3
(Ro_2+b)
Ro_2
$X_{R=0}$
(Ro_3+c)
Wr
(Ro_3+e)
AXIS EACH SECTION
$Ro_3 + R$
$Ro_2 + R$
Xr
SEC IV
SEC III
SEC II
SEC VII
SEC I



TIDAL SECTION OF RARITAN RIVER AREA AND "AK" VS. DISTANCE

FIGURE 13

of the appropriate equations for each of the seven sections into which the Raritan River has been divided. Table 12 presents a definition of symbols for these equations. It should be noted that a mean algae effect has been included in the Raritan model.

A matrix solution was employed to develop the computer program for water quality in the Raritan River. The dissolved oxygen deficit matrix of unknown coefficients is generated from the BOD matrix by replacing the values of:

S by SD

V by VD

Ir by Ia

Kr by Ka

Gr by Ga

A computer program has been developed at New York University for the tidal portion of Raritan River.

TABLE 10

RARITAN RIVER
TIDAL SECTION

Boundary Conditions

1. Flux at $XR = 0$
2. Concentration equality at $XR = a = R_{o_2}$
3. Flux at $XR = a = R_{o_2}$
4. Concentration at $R_{o_3} = R_{o_2} + b$
5. Flux at $R_{o_3} = R_{o_2} + b = X_o$
6. Concentration $R_{o_3} = X_o$
7. Concentration at $R_{o_4} = R_{o_3} + c$
8. Flux at $R = R_{o_3} + c$
9. Concentration at $R_{o_3} + e$
10. Concentration at $X = f$
11. Flux at $X = f$
12. Flux at $X = d$
13. Concentration at $R_{o_2} + h$
14. Flux at $R_{o_2} + h$

NOTE: 14 unknown coefficients and 14 equations.

TABLE 11

RARITAN RIVER TIDAL SECTION

Section Number	BOD EQUATION	DEFICIT EQUATION
1	$BOD(1) = B_1 e^{S_1 X_R} + C_1 e^{V_1 X_R}$	$DEF_{(1)} = G_1 e^{SD_1 X_R} + H_1 e^{VD_1 X_R} + yP_1$
2	$BOD(2) = B_2 I_{r_2}(R) + C_2 K_{r_2}(R)$	$DEF_{(2)} = G_2 I_{a_2}(R) + H_2 K_{a_2}(R) + yP_2$
3	$BOD(3) = B_3 I_{r_3}(R) + C_3 K_{r_3}(R)$	$DEF_{(3)} = G_3 I_{a_3}(R) + H_3 K_{a_3}(R) + yP_3$
4	$BOD(4) = B_4 I_{r_4}(R) + C_4 K_{r_4}(R)$	$DEF_{(4)} = G_4 I_{a_4}(R) + H_4 K_{a_4}(R) + yP_4$
5	$BOD(5) = B_5 e^{S_5 X} + C_5 e^{V_5 X}$	$DEF_{(5)} = G_5 e^{SD_5 X} + H_5 e^{VD_5 X} + yP_5$
6	$BOD(6) = B_6 e^{S_6 X} + C_6 e^{V_6 X}$	$DEF_{(6)} = G_6 e^{SD_6 X} + H_6 e^{VD_6 X} + yP_6$
7	$BOD(7) = B_7 I_{r_7}(R) + C_7 K_{r_7}(R)$	$DEF_{(7)} = G_7 I_{a_7}(R) + H_7 K_{a_7}(R) + yP_7$

TABLE 12

RARITAN RIVER
TIDAL SECTION

$$yp_1 = FAC(1)\ [\, B_1 e^{S_1 X} + C_2 e^{V_1 X} \,] + Dp_1$$

$$yp_1' = FAC(1)\ [\, B_1 S_1 e^{S_1 X} + C_1 V_1 e^{V_1} \,]$$

$$yp_2 = FAC(2)\ [\, B_2 I_{r_2} + C_2 K_{r_2} \,] + Dp_2$$

$$yp_2' = FAC(2)\ [\, B_2 I'_{r_2} + C_2 K'_{r_2} \,]$$

$$yp_3 = FAC(3)\ [\, B_3 I_{r_3} + C_3 K_{r_3} \,] + Dp_3$$

$$yp_3' = FAC(3)\ [\, B_3 I'_{r_3} + C_3 K'_{r_3} \,]$$

$$yp_4 = FAC(4)\ [\, B_4 I_{r_4} + C_4 K_{r_4} \,] + Dp_4$$

$$yp_4' = FAC(4)\ [\, B_4 I'_{r_4} + C_4 K'_{r_4} \,]$$

$$yp_5 = FAC(5)\ [\, B_5 e^{S_5 X} + C_5 e^{V_5 X} \,] + Dp_5$$

$$yp_5' = FAC(5)\ [\, B_5 S_5 e^{S_5 X} + C_5 V_5 e^{V_5 X} \,]$$

$$yp_6 = FAC(6)\ [\, B_6 e^{S_6 X} + C_6 e^{V_6 X} \,] + Dp_6$$

$$yp_6' = FAC(6)\ [\, B_6 S_6 e^{S_6 X} + C_6 V_6 e^{V_6 X} \,]$$

TABLE 12

(Continued)

RARITAN RIVER

TIDAL SECTION

To evaluate $yp_{(i)}(X)$ and $yp'_{(i)}(X)$, substitute the desired value of X into the equation for $yp(i)$ or $yp'(i)$:

$$yp_7 = FAC(7) \; [\, B_7 I_{r_7} + C_7 K_{r_7} \,] + Dp_7$$

$$yp'_7 = FAC(7) \; [\, B_7 I'_{r_7} + C_7 K'_{r_7} \,]$$

TABLE 12

(Continued)

Where:

(i) = Section number:

$$I_{r(i)} = R^{vv(i)} I_{v}(g_r r)_{(i)}$$

$$K_{r(i)} = R^{vv(i)} K_{vv}(g_r R)_{(i)}$$

$$I_{g(i)} = R^{vv(i)} I_{vv}(g_a R)_{(i)}$$

$$K_{g(i)} = R^{vv(i)} K_{vv}(g_a R)_{(i)}$$

$$I_{vv}(g_r R) = \sum_{K=0}^{\infty} \frac{(g_r R/2)^{2K+vv}}{K!\ \Gamma\ (K+V+1)}$$

$$K_{vv}(g_r R) = \frac{\pi}{2} \quad \frac{I_{-v}(g_r R) - I_{vv}(gR)}{\text{Sin}\ vv\ \pi}$$

TABLE 12

(Continued)

$I_v(g_a R)$ and $K_v(g_a R)$ ⟶ replace g_r by g_a

$g_r = (RK/E)^{1/2}$

$g_a = (AK/E)^{1/2}$

$$V = \frac{QR_o}{2EA_o}$$

I' = Gamma function

R = Distance from origin in each section

X = Distance from $X = 0$ in South River

X_R = Distance from dam in Raritan River

$$\left.\begin{array}{l} S \\ V \\ SD \\ VD \end{array}\right\} = \text{Standard Roots}$$

$$D_p = \frac{R_a - P_a}{AK}$$

$$yp = \frac{F \cdot DK}{AK - RK} \left[\text{BOD solution} \right] + D_p$$

Middle Hudson Estuary

The middle Hudson Estuary extends from roughly Catskill, New York, to Yonkers, New York. In essence, it joins the upper Hudson Estuary with the North River.

Figures 14 and 15 present the cross-sectional area and reaeration coefficient as functions of distance. It may be observed that the middle Hudson Estuary is characterized by a varying cross-sectional area as a function of distance between mile points 86 and 118 . Downstream of mile point 86 it is possible to consider the Estuary composed of a number of constant cross-sectional area segments.

Water quality data, and information on waste inputs and dispersion in this area are relatively lacking. This void suggests that a model of the middle Hudson Estuary incorporating simplifying assumptions is the most appropriate for an immediate first cut analysis of water quality.

A schematic illustration of a simplified model for water quality in the middle Hudson is presented on Figure 16 . It consists of four (4) constant cross-sectional area segments with provision for waste

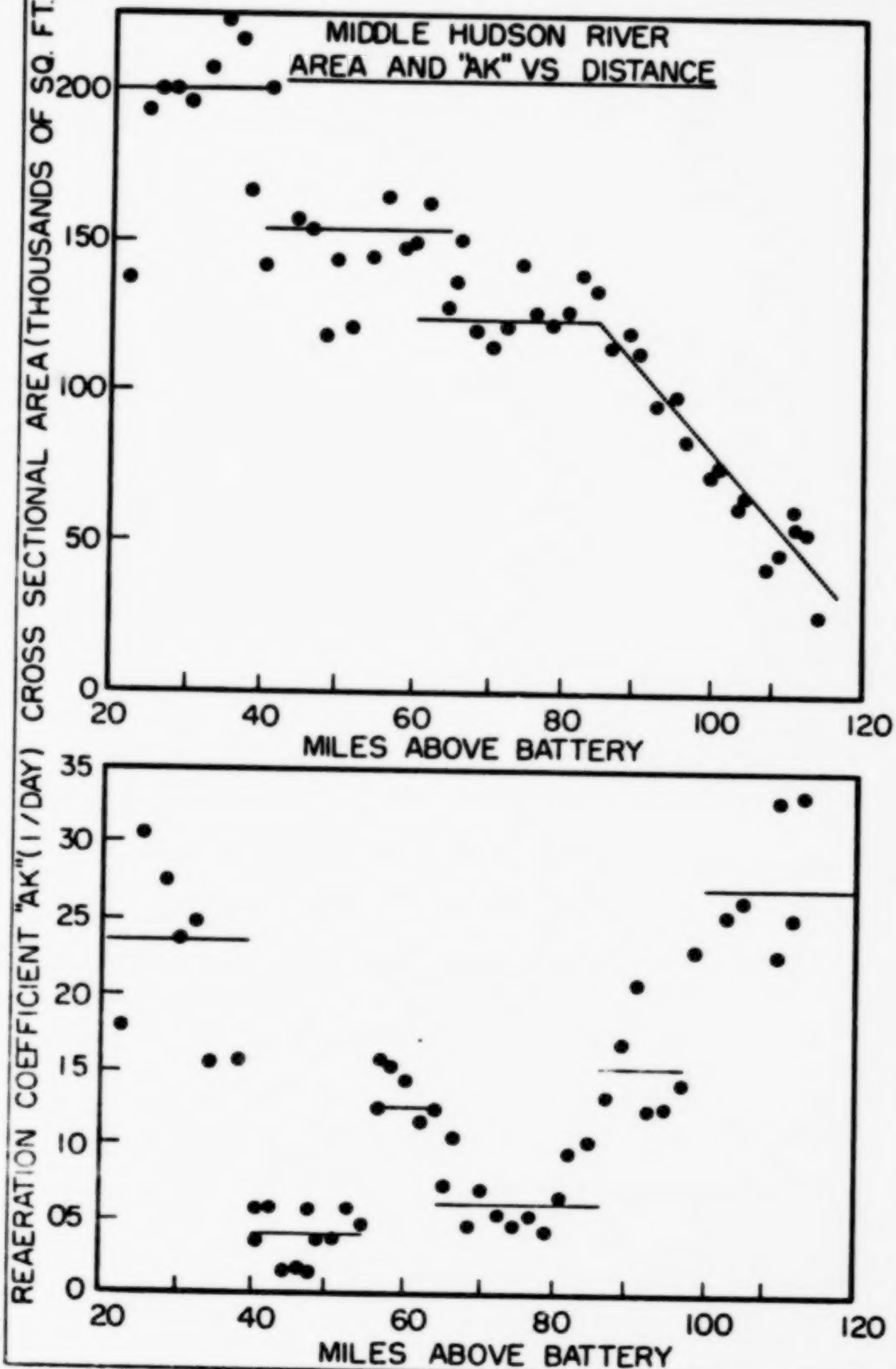
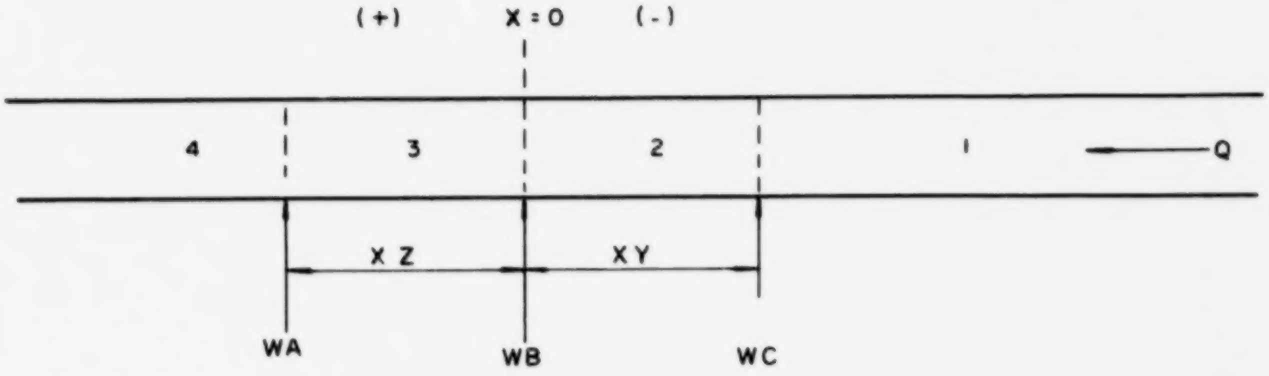

MIDDLE HUDSON RIVER
AREA AND "AK" VS DISTANCE
CROSS SECTIONAL AREA (THOUSANDS OF SQ. FT.)
0
50
100
150
200
20
40
60
80
100
120
MILES ABOVE BATTERY
REAERATION COEFFICIENT "AK" (1/DAY)
0
05
10
15
20
25
30
35
20
40
60
80
100
120
MILES ABOVE BATTERY

FIGURE 14 & 15

SCHEMATIC OF MIDDLE HUDSON RIVER ESTUARY MODEL


(+)
X = 0
(-)
4
3
2
1
Q
X Z
X Y
WA
WB
WC

NOTE: SEE TEXT FOR EXTENT & APPLICATION

FIGURE 16

inputs at three (3) locations.

A matrix system of evaluating the non-zero unknown coefficients has been employed in the middle Hudson Estuary model. The specific boundary conditions are:

Boundary Condition #	Location	Type
1	$X = XY$	$L_1 = L_2$
2	$X = XY$	Mass Balance
3	$X = 0$	$L_2 = L_3$
4	$X = 0$	Mass Balance
5	$X = XZ$	$L_3 = L_4$
6	$X = XZ$	Mass Balance
7	$X = +$	$L_4 = 0$
8	$X = -$	$L_1 = 0$

A complete program for the middle Hudson Estuary is presented in the appendix of this report.

As indicated, the simplified middle Hudson Estuary model will provide an excellent tool for obtaining an initial evaluation of water quality parameters and inputs for the entire region between Catskill, New York and Yonkers, New York. As additional water quality data becomes available, and as more information on waste loads entering the system are obtained, it is desireable to employ more refined mathematical models.

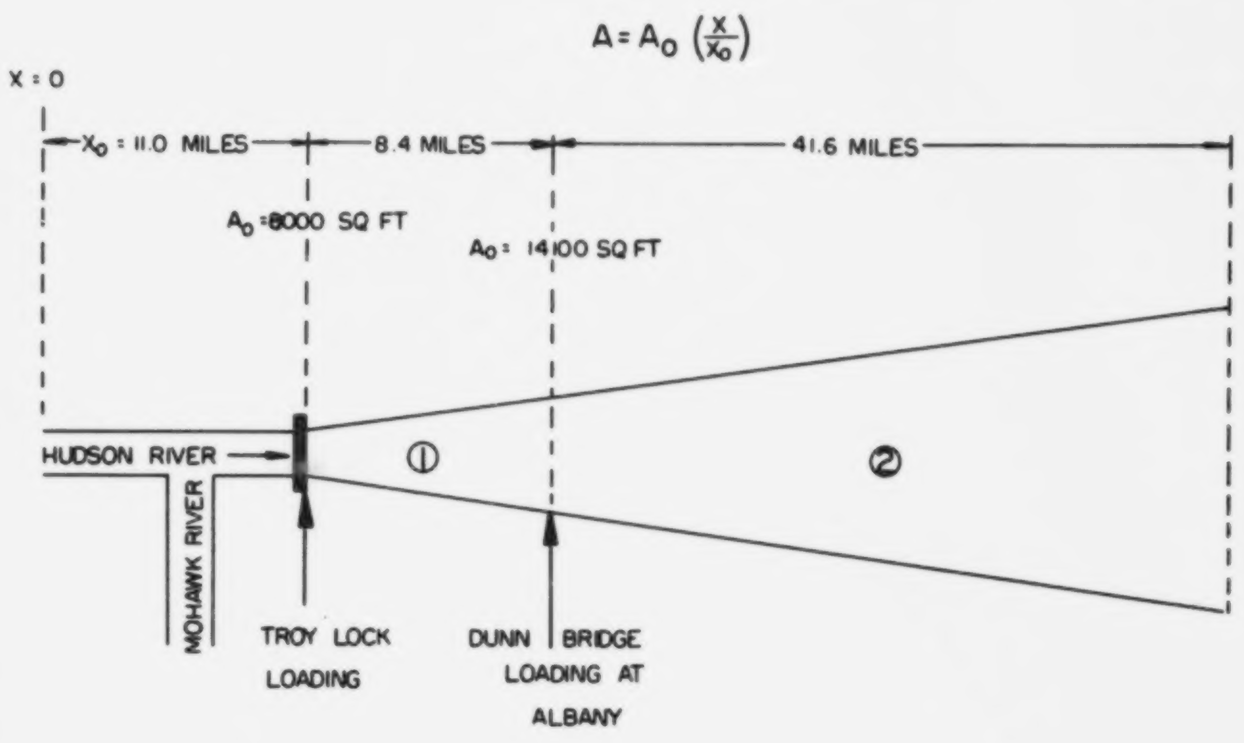
Upper Hudson River System

The upper Hudson River system may be considered to extend from the Federal lock and dam at Troy approximately 50 miles downstream to the vicinity of Saugerties, New York. This reach is characterized by tidal oscillation and reversal but is primarily fresh water in nature. Analysis of available water quality data indicate that the tidal dispersion effect, the magnitude of which is represented by the coefficient, " E ", is minimal in the region. As a result, the mathematical model is somewhat simplified by eliminating the dispersion coefficient from the development.

Figure (17) is a schematic diagram of the upper Hudson River system. Figure (18) presents the cross-sectional area and mean depth distributions. The area variation may be defined by cylindrical coordinates of the form:

$$A = A_o \left(\frac{R}{R_o} \right)$$

In which A is the cross-sectional area at any distance, R, and A_o is the area at R_o measured from an imaginary origin. The system was divided into two (2) segments to account for the variation in mean depth as indicated in Figure (18). The average depth in each segment was taken as the constant value indicated on the diagram for computation of the atmospheric reaeration coefficient, " AK" . The average tidal velocity was used to calculate this coefficient.


$A = A_0 \left(\frac{X}{X_0}\right)$
X = 0
X_0 = 11.0 MILES
8.4 MILES
41.6 MILES
A_0 = 8000 SQ FT
A_0 = 14100 SQ FT
HUDSON RIVER
MOHAWK RIVER
①
②
TROY LOCK LOADING
DUNN BRIDGE LOADING AT ALBANY

UPPER HUDSON RIVER ESTUARY

FIGURE 17

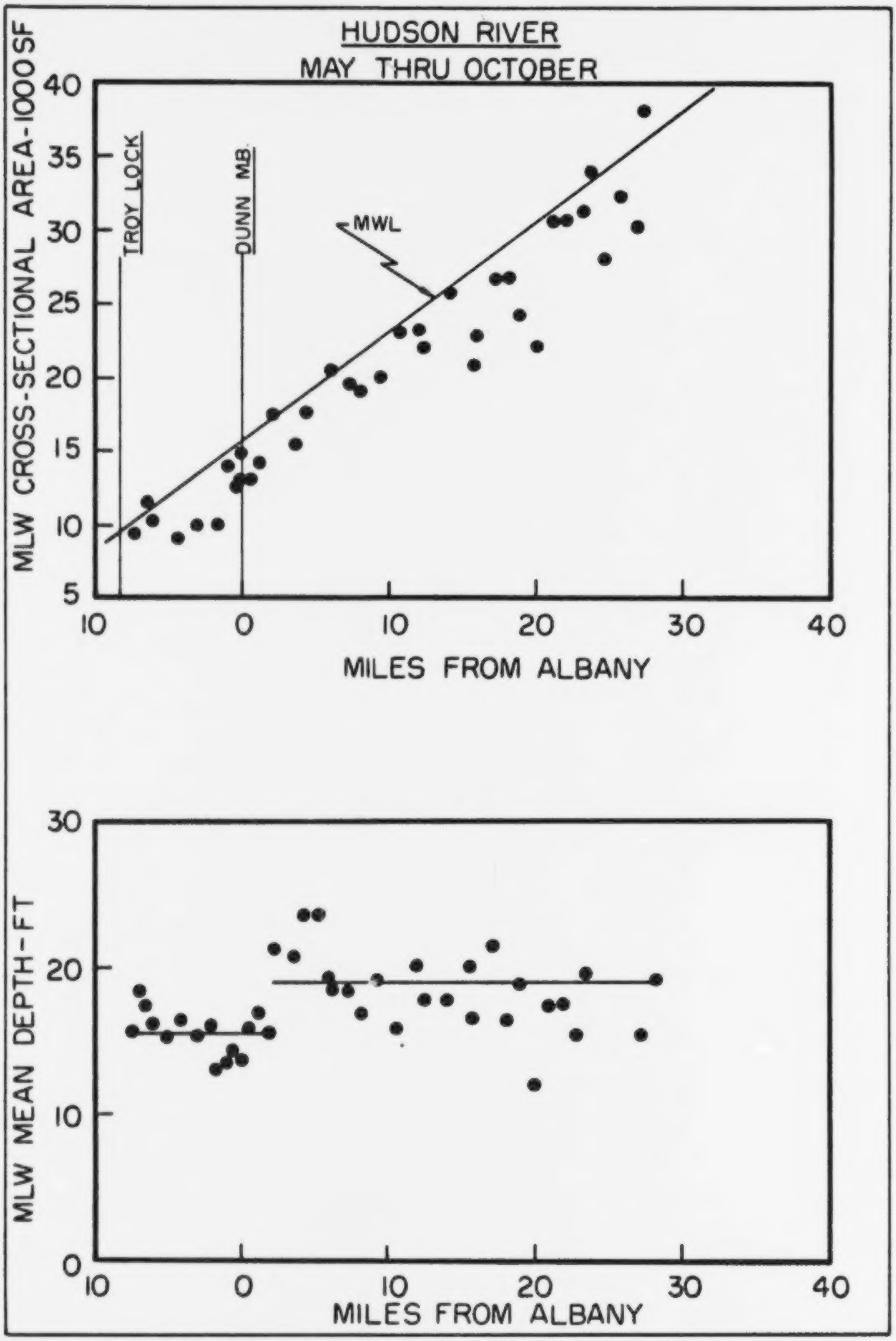

HUDSON RIVER
MAY THRU OCTOBER
MLW CROSS-SECTIONAL AREA-1000SF
40
35
30
25
20
15
10
5
TROY LOCK
DUNN MB
MWL
10
0
10
20
30
40
MILES FROM ALBANY
MLW MEAN DEPTH-FT
30
20
10
0
10
0
10
20
30
40
MILES FROM ALBANY

FIGURE 18

As tidal dispersion was not a significant factor in the mathematical development, the basic differential equations were integrated directly to final solution. The unknown arbitrary constants, "B" and "C" for BOD relationships and "G" and "H" for deficit functions, were readily determined from boundary and initial conditions. Matrix solution for this system was not required. The final solutions were programmed for digital computation by Hydroscience, Inc. and the program listing is presented in the appendix.

Waste waters enter the upper Hudson River system at numerous locations between Troy and the lower boundary of Albany County. However, the discharges are roughly concentrated and were considered to enter the main stream at two primary locations; the Federal Lock at Troy and the Dunn Memorial Bridge at Albany. The domestic waste loadings are carbonaceous and nitrogenous in nature. The deficit distribution associated with both the carbonaceous and nitrogenous fraction of the total BOD was individually computed for each of the two primary loading locations. The BOD reaction coefficients, "RK" and "DK" were assigned carbonaceous and nitrogenous values as appropriate. In addition to the major loadings, allowance was made for BOD and oxygen deficit entering the system with waters from above the dam. The method of superposition can be applied and the individual deficit profiles accumulated to yield a total distribution.

Regional Water Quality Models

The water quality models thus far presented are for relatively small subsystems of the waterways under study. These small models are excellent tools for evaluating parameters and loading data, as well as providing a basis upon which a rational field program can be developed.

In addition to the small subsystem models, three large water quality models have been developed which can be employed to characterize water quality in the following major regions:

1. New York Harbor Complex
    a) East River (upper and lower)
    b) Harlem River
    c) North River
    d) Upper New York Harbor
    e) Kill Van Kull
    f) Newark Bay
    g) Arthur Kill
2. Hudson Estuary Model
    a) Hudson River from the Troy Lock to Yonkers
3. Complete Study Area
    a) Hudson Estuary Model
    b) New York Harbor Complex
    c) Raritan River

The techniques employed to develop the mathematical models for water quality are described under the section entitled, " Method for Evaluation and Presentation of Boundary Conditions for Complex Estuaries. " The specific approach employed to developing a computer program leads to a single program which can be employed to generate all three of the large water quality models. In essence, the water quality systems to be studied can be mapped in the computer program.

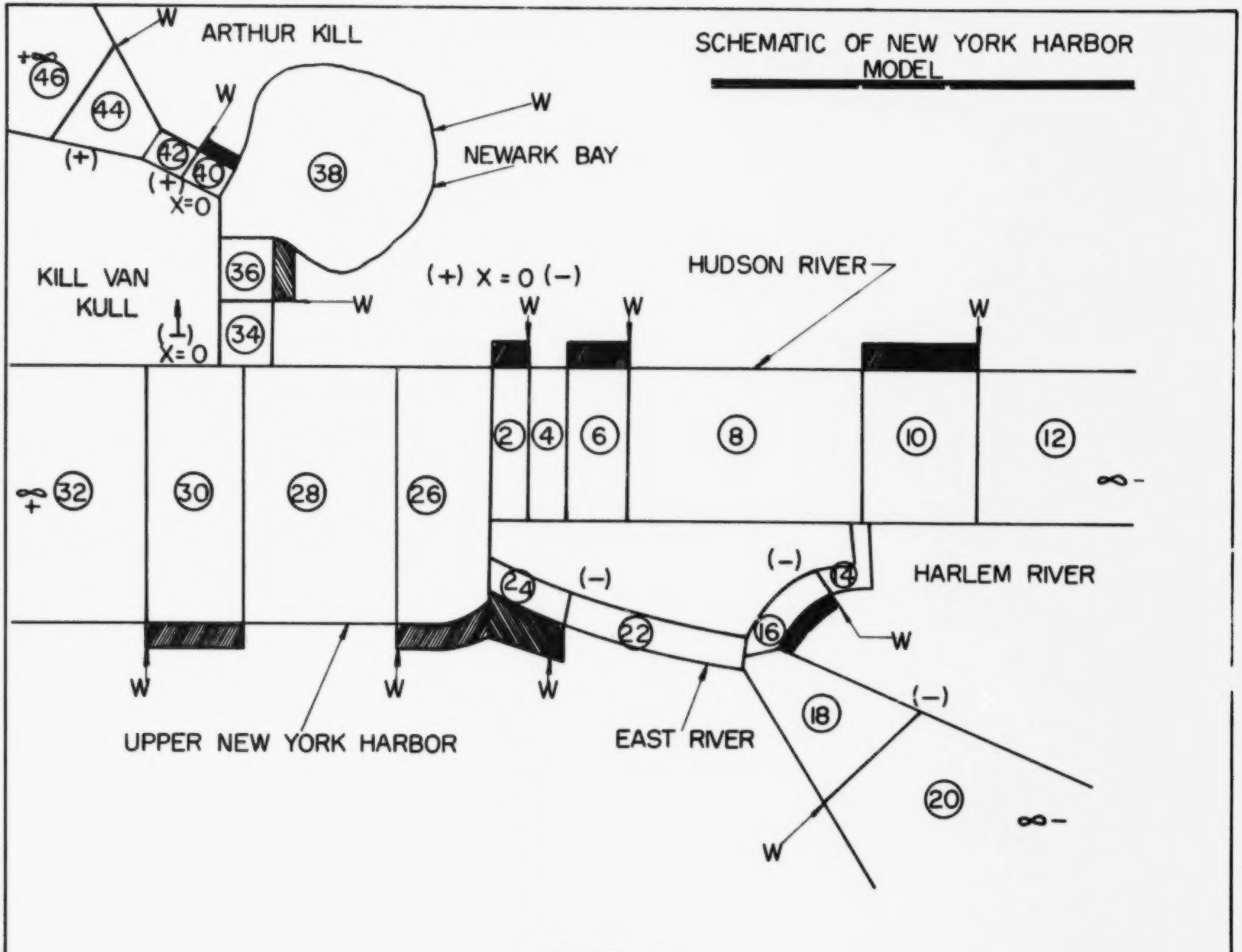
New York Harbor Complex

Figure 19 is a schematic representation of the mathematical model for water quality in the New York Harbor Complex. The section numbers that have been assigned are arbitrary. Table 13 indicates the functional form of the equations for BOD and dissolved oxygen deficit in each section. In addition, the sections which are exceptions to the general equations are specifically defined.

The coordinate systems used in this model are :

Number	Origin	Section
1	XA = 0 at Battery	2 to 16, 22 to 32
2	XB = 0 at Arthur Kill and Newark Bay	40 and 42
3	XC = 0 at Kill Van Kull and Newark Bay	36 and 34
4	R = Ro (18) at Upper East River	18 and 20
5	R = Ro (44) at Arthur Kill	44 and 46

Table 14 presents a specific listing of the appropriate boundary classification applicable to each section. The sections I upstream and K downstream have been identified. The boundary equations are sequentially numbered. The system generates 41 unknown coefficients and 41 boundary



SCHEMATIC OF NEW YORK HARBOR MODEL

ARTHUR KILL
NEWARK BAY
KILL VAN KULL
HUDSON RIVER
HARLEM RIVER
EAST RIVER
UPPER NEW YORK HARBOR
(+) X = 0 (−)
(+) X=0
(+)
(−)
X=0
+∞
∞−
∞+
W
46
44
42
40
38
36
34
32
30
28
26
24
22
2
4
6
8
10
12
14
16
18
20

FIGURE 19

equations.

Employing Tables 13 and 14 in conjunction with Tables 4, 5, and 6, and the example estuary problem, a computer program can be written for evaluating the unknown coefficients and calculating the required profiles for BOD and dissolved oxygen deficit for the New York Harbor Complex.

TABLE 13

FUNCTIONAL FORMS FOR NEW YORK HARBOR COMPLEX WATER QUALITY MODEL

(Sections illustrated on Figure 19)

Constant Area

Sections 2 to 16

22 to 36

40 to 42

Variable Area $A = Ao (\frac{R}{Ro})^2$

Sections 44, 46, and 18 and 20

Mixed Volumes:

Section 38 (Equation 47)

Note: Equation 45 (Section 20 and 12)

Equation 46 (Section 32 and 46)

TABLE 14

BOUNDARY CLASSIFICATIONS NEW YORK HARBOR COMPLEX

(Sections Illustrated on Figure 19)

Boundary Classification	I	K	KK	J (Boundary No)
1 - 5	4	2	--	2
	6	4	--	4
	8	6	--	6
	14	16	--	8
	22	24	--	10
	26	28	--	12
	36	34	--	14
	42	44	--	16
	40	42	--	18
2 - 6	12	10		20
	20	18		22
3 - 7	30	32		24
	44	46		26
8	10	14	8	27
9	24	26	8	28
	16	22	18	29
	28	30	34	30

TABLE 14

(Continued)

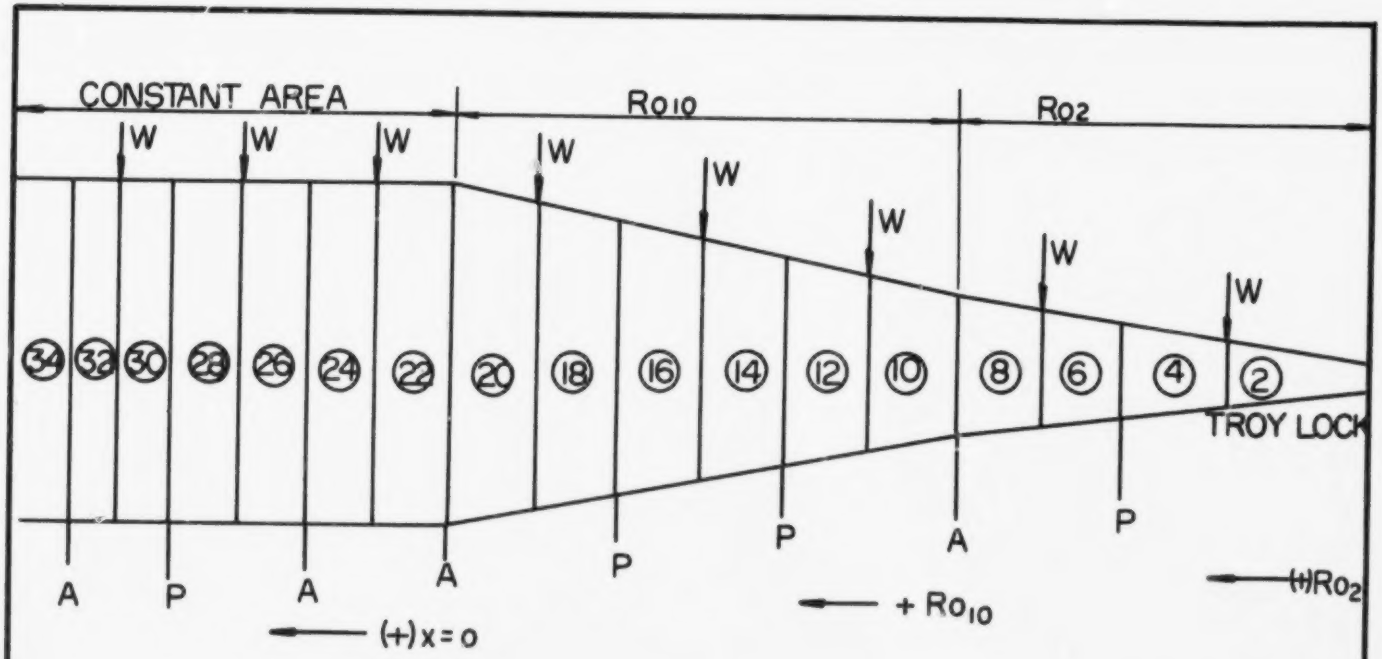
Boundary Classification	I	K	KK	J (Boundary No)
11	38	36	40	31
4	38	36	--	32
	38	40	--	33
1	10	14	--	34
	10	8	--	35
	16	18	--	36
	16	22	--	37
	24	26	--	38
	26	2	--	39
	28	30	--	40
	34	30	--	41

Hudson Estuary Model

Figure 20 contains a schematic illustration of the water quality model for the Hudson Estuary extending from the New York Harbor model to the Troy lock.

The section of the model extending from the Troy lock to Saugerties, New York is characterized by an expanding area. A change in the reaeration coefficient is also observed in this portion of the estuary. The rate of area expansion changes downstream from Saugerties, as shown on Figure 21. Beginning at mile point 85 three constant area sections have been employed. The location of known parameter change have also been indicated on Figure 21.

Table 15 presents the appropriate area functions for the various sections in the middle Hudson estuary and Table 16 lists the specific boundary conditions to be applied between sections. The sections I upstream and K downstream have been identified.


CONSTANT AREA
Ro10
Ro2
W
W
W
W
W
W
W
W
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
TROY LOCK
A
P
A
A
P
P
A
P
(+)x = o
+ Ro10
(+)Ro2

NOTE: P - PARAMETER CHANGE
A = AREA FUNCTION CHANGE
W = POINT WASTE INPUT
ALL SECTIONS HAVE PROVISION
FOR UNIFORM LOAD, BOTTOM
DEPOSITS AND ALGAE.

SCHEMATIC OF HUDSON ESTUARY MODEL. TROY, N.Y TO YONKERS
FIGURE

FIGURE 20

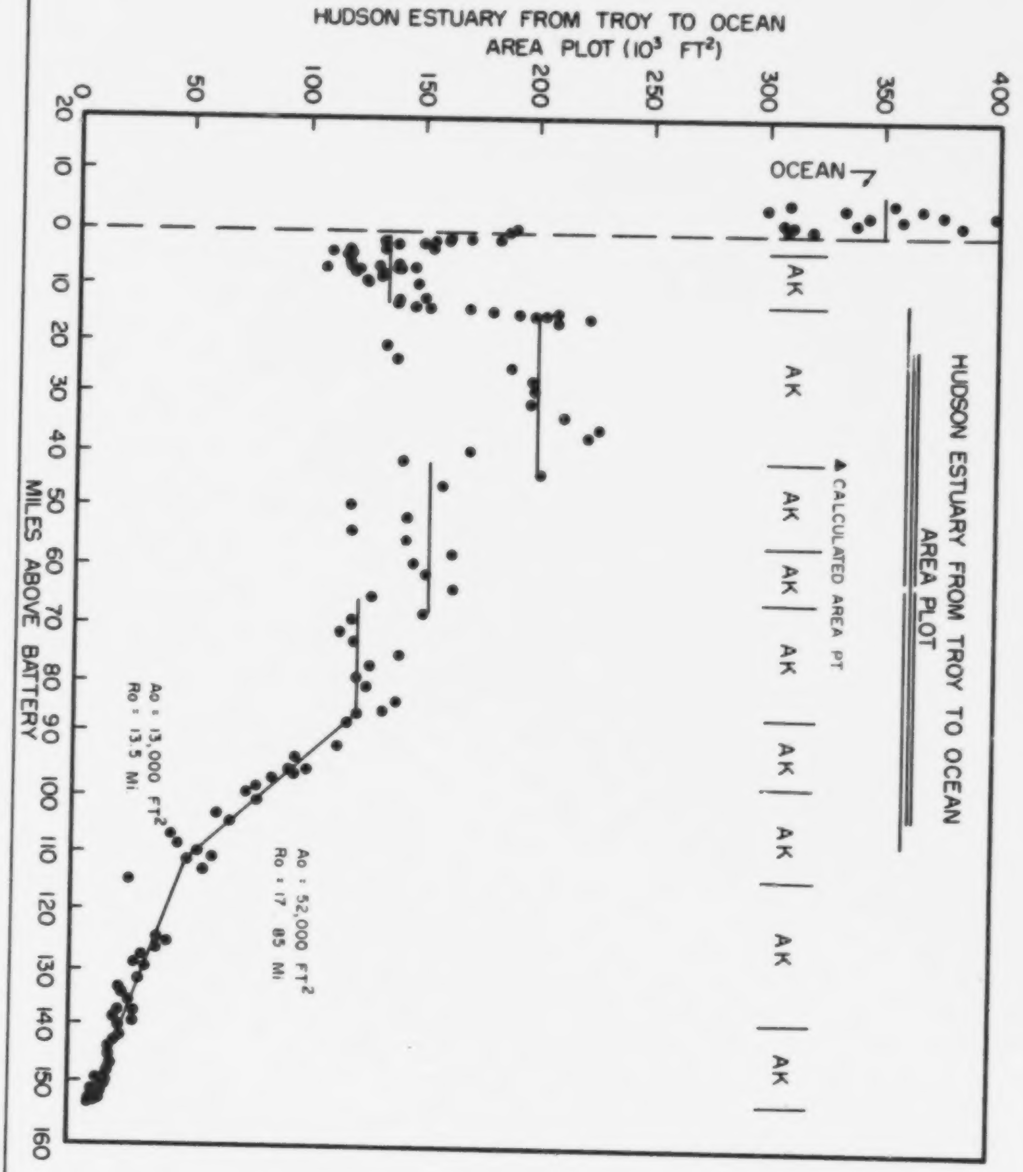

HUDSON ESTUARY FROM TROY TO OCEAN
AREA PLOT (10³ FT²)
0
50
100
150
200
250
300
350
400
20
10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
MILES ABOVE BATTERY
OCEAN
AK
AK
AK
AK
AK
AK
AK
AK
AK
HUDSON ESTUARY FROM TROY TO OCEAN
AREA PLOT
▲ CALCULATED AREA PT
Ao = 13,000 FT²
Ro = 13.5 Mi
Ao = 52,000 FT²
Ro = 17.85 Mi

FIGURE 21

TABLE 15

FUNCTIONAL FORMS TO BE USED IN WATER QUALITY MODEL OF HUDSON ESTUARY

(Sections Illustrated on Figure 20)

Expanding Area $A = Ao \left(\frac{R}{Ro} \right)$

Sections 2 to 20

Constant Area

Sections 22 to 36

Note: Section 36 (Use Equation 46)

TABLE 16

BOUNDARY CLASSIFICATIONS FOR HUDSON ESTUARY

(Sections Illustrated on Figure 20)

Boundary Classification	I	K	KK	J (Boundary No)
1 - 5	2	4	--	2
	4	6	--	4
	6	8	--	6
	8	10	--	8
	10	12	--	10
	12	14	--	12
	14	16	--	14
	16	18	--	16
	18	20	--	18
	20	22	--	20
	22	24	--	22
	24	26	--	24
	26	28	--	26
	28	30	--	28
	30	32	--	30
	32	34	--	32
3 - 7	34	36	--	34
10	--	2	--	35

Hudson Estuary, Harbor Complex, and Raritan River Model

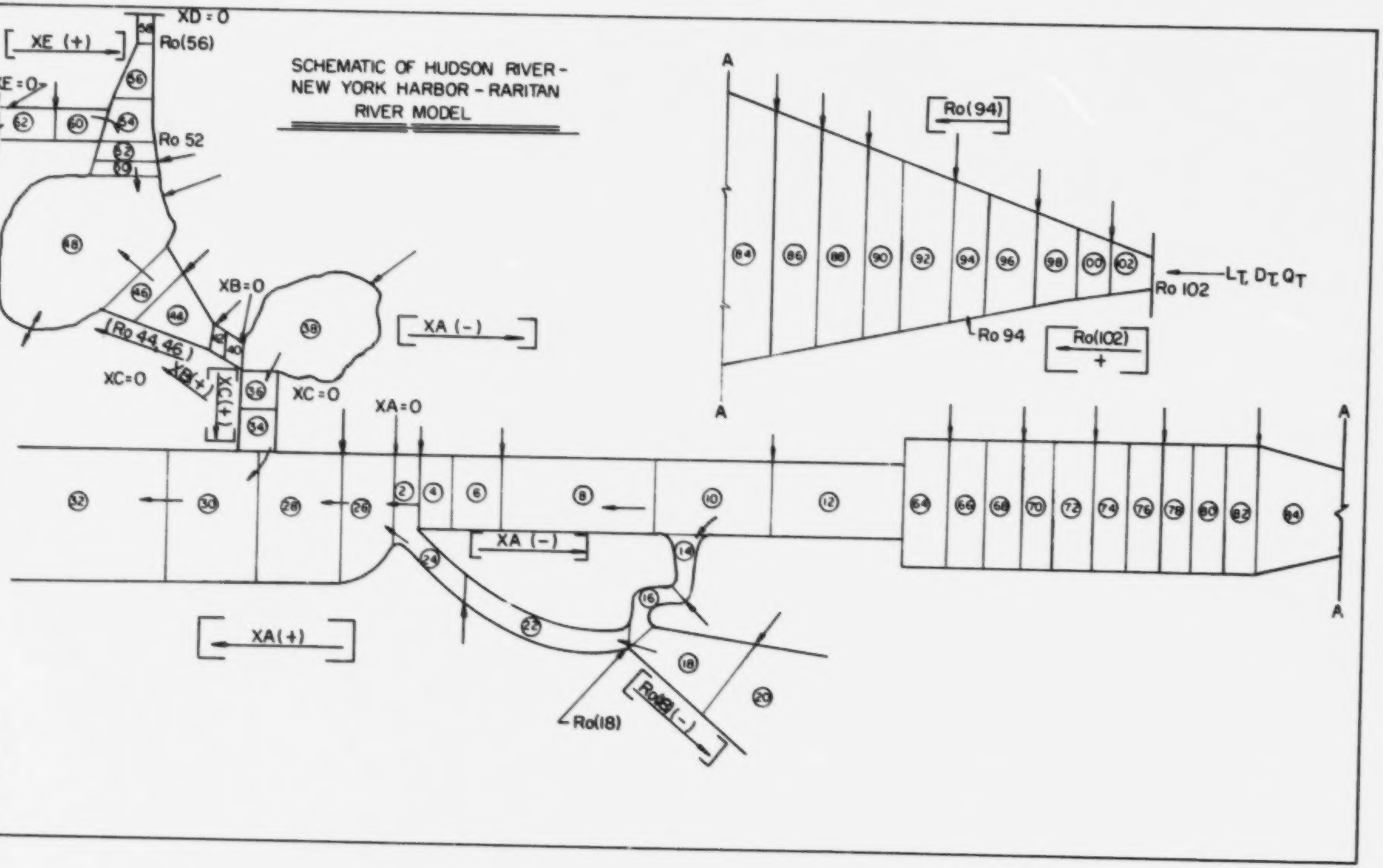
Figure 22 is a schematic diagram of a single mathematical model for water quality in the Hudson Estuary from Troy, New York to the Atlantic Ocean including the waters of New York Harbor and the Raritan River. This single water quality model will describe the influence of an input in any segment on the water quality in any other section of the system.

The system diagrammed in Figure 22 has been segmented into fifty-one sections. Some allowance has been made in the middle Hudson Estuary for sections which can be employed to include changes in parameters. Information on the values of parameters in this portion of the study area appeared weak, thus provision was made for additional sections to provide flexibility.

The location of section boundaries are in all cases measured from the point of origin of the applicable coordinate system. Eleven coordinate systems were employed in the model. They are defined at:

Number	Origin	Sections
1	XA = O @ Battery	2 to 16 26 to 30 64 to 82
2	XB = O @ Arthur Kill and Newark Bay	40 & 42
3	XC = O @ Kill Van Kull and Newark Bay	36 & 34
4	XD = O @ Fieldville Dam	58
5	XE = O @ Duhernal Dam	60 & 62
6	R = Ro (56) @ Raritan River	56 & 54
7	R = Ro (52) @ Raritan and South River	52 & 50
8	R = Ro (94) @ Saugerties	84 to 94
9	R = Ro (102) @ Troy	96 to 102
10	R = Ro (18) @ Upper East River	18 & 20
11	R = Ro (44) @ Arthur Kill	44 & 46

The direction of axis for the various bodies of water has been indicated on Figure 22. Table 17 presents the specific boundary conditions and classifications for the water quality model schematically illustrated in Figure 22. Table 18 indicates the appropriate functional form for each section.



SCHEMATIC OF HUDSON RIVER - NEW YORK HARBOR - RARITAN RIVER MODEL

XD = 0
Ro(56)
XE (+)
XE = 0
Ro 52
XB = 0
Ro 44, 46
XB (+)
XC = 0
XC (+)
XC = 0
XA = 0
XA (-)
XA (-)
XA (+)
Ro(18)
Ro(18) (-)
Ro(94)
Ro 94
Ro(102)
+
Ro 102
L_T, D_T, Q_T
A
A
A
A
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100 102

FIGURE 22

TABLE 17

SPECIFIC BOUNDARY CLASSIFICATIONS FOR WATER QUALITY MODEL FROM TROY, NEW YORK TO THE ATLANTIC OCEAN

(Sections Illustrated on Figure 22)

Boundary Classification	I	K	KK	J (Boundary No)
1 and 5	4	2	--	2
	6	4	--	4
	8	6	--	6
	12	10	--	8
	64	12	--	10
	66	64	--	12
	68	66	--	14
	70	68	--	16
	72	70	--	18
	74	72	--	20
	76	74	--	22
	78	76	--	24
	80	78	--	26
	82	80	--	28
	84	82	--	30
	86	84	--	32
	88	86	--	34
	90	88	--	36
	92	90	--	38
	94	92	--	40
	96	94	--	42
	98	94	--	44
	100	98	--	46
	102	100	--	48
	14	16	--	50
	22	24	--	52

TABLE 17

(Continued)

Boundary Classification	I	K	KK	J (Boundary No)
1 and 5	26	28	--	54
	36	34	--	56
	40	42	--	58
	42	44	--	60
	44	46	--	62
	58	56	--	64
	56	54	--	66
	52	50	--	68
	62	60	--	70
10	--	102	--	71
	--	58	--	72
	--	62	--	73
5	36	38	--	74
	40	38	--	75
	46	48	--	76
	50	48	--	77
11	36	40	38	78
12	46	50	48	79

TABLE 17

(Continued)

Boundary Classification	I	K	KK	J (Boundary No)
1	2	26	--	80
	28	30	--	81
	28	34	--	82
	24	26	--	83
	10	8	--	84
	10	14	--	85
	16	22	--	86
	18	22	--	87
	60	52	--	88
	54	52	--	89
2 and 6	20	18	--	91
3 and 7	30	32	--	93
9	10	8	14	94
	2	26	24	95
	18	22	16	96
	28	30	34	99
	60	52	54	98

TABLE 18

SPECIFIC FUNCTIONAL FORMS TO BE USED IN WATER QUALITY MODEL FROM TROY, NEW YORK TO THE OCEAN

(Sections Illustrated on Figure 22)

Constant Area

Sections 2 to 16
64 to 82
22 to 36
40, 42, 62, and 58

Expanding Area $A = Ao \frac{R}{Ro}$

Sections 84 to 102
50 to 56

Expanding Area $A = Ao \left(\frac{R}{Ro} \right)^2$

Sections 18, 20, 44, and 46

Bays

Sections 38 and 42 (Use Equation 47)

Note: Section 20 (Use Equation 45)
Section 32 (Use Equation 46)

LOADS AND SYSTEM INPUTS

Mathematical models have been developed which can be employed to describe water quality in the various waterways and components of the system under study. Where practical, these models have been developed to permit evaluation of water quality from a consideration of external system input without recourse to the use of observed water quality data. In order to effectively employ the mathematical models, it is necessary to evaluate external system loads, such as waste water discharges.

Efforts have been made by the participants in this phase of the study to collect and evaluate data on wastes entering the system. A summary of the available information is presented in Tables 19 to 23 . The specific information on waste inputs and locations have been grouped to provide inputs for the mathematical models. The waste input information available for the system is at best an approximation. A significant effort is required to develop reliable estimates of inputs into the system.

The problem of location and evaluation of waste discharge magnitude is extremely complex in the area under study. Problems generally encountered in evaluating storm overflow, urban runoff, and natural pollutional loads is further complicated by the extremely high population density of portions of the study area, the variability of land uses in the study area, and the relative absence of collection and treatment facilities for wastes.

TABLE 19

NEW YORK HARBOR

North River Loads

Component or System	Location from Battery (miles)	Magnitude of Load (#/ day)	
		(BOD)	(DEF)
East River	1.8	88,000	2,200
East River	4.3	136,400	5,000
East River	9.4	44,200	6,000
East River	11.7	72,000	9,000
Upper Bay	3.1	140,000	15,000
Upper Bay	4.2	100,000	10,000
Upper Bay	1.5	52,000	5,500
North River	1.1	42,500	7,300
North River	7.0	14,600	3,900
North River	15.5	72,000	11,600
North River	20.0	19,000	4,300
North River	4.0	93,000	3,000
North River	6.0	93,000	3,000
North River	8.0	93,000	3,000
North River	10.0	93,000	3,000

TABLE 20

ARTHUR KILL DOMESTIC PLANTS

Location (Miles)	Pounds BOD per day
1.166	69,500
2.528	25,810
7.758	30,900
8.048	2,818
11.828	3,000

TABLE 21

ARTHUR KILL SYSTEM

Industrial Loads

Source	Load **	Average Distance (miles)
Hess Chevron	7,190	9.59
Kopps Wood U. S. Metals F. M. C.	770	6.75
American Cynamid, Linden Citgo General Aniline DuPont Grasselli	42,207	3.45
Humble Oil	72,400	1.38
Archer Daniels Procter & Gamble	12,200	.625

Zero (0) located 1800 yards due East of Shooter's Island

(All locations related to zero (0))

** LOAD = $BOD \times 1.5 + 4.5\ NH_3$

TABLE 22

MUNICIPAL LOADS

Middle Hudson River

Load	Location from Battery (miles)	Five-day BOD pounds / day
Yonkers	16	52, 400
Pearl River	26	1, 300
Ossinning	33	6, 700
Peekskill	46	6, 200
Beacon-Newburgh	62	8, 050
Poughkeepsie	72	6, 020
Kingston	91	8, 300
Saugerties	96	700
Catskill	110	1, 300
Albany - Troy area	Federal Lock at Troy	35, 100(1)
	Dunn Memorial Bridge Albany, New York	63, 800(1)
	BOD over lock	35, 000(2)

NOTE: (1) 80% of these values can be used for nitrogenous oxygen demand

(2) Limited BOD data indicated 1.5 ppm BOD in flow over lock

TABLE 23

LOAD LOCATIONS

Tidal Section of Raritan River

Component or System	Location (Miles) From Fieldville or Duhernal Dams	Magnitude (pounds/day)
Raritan River	13.3	550
Raritan River	14.3	3,000
Raritan River	15.2	36,600
Raritan River	15.6	550
Raritan River	16.4	7,900
South River	.1	300
South River	3.2	6,900

There are essentially two (2) methods available to investigators for evaluating system inputs. The most reliable method consists of a field program which actually measures the waste entering the system. The second approach is a paper study of the population and equivalent population which discharges wastes into the system. In using either approach for evaluation of waste loadings, it is necessary to determine the location of waste discharges, and the magnitude of the various discharged substances which influence water quality.

Dissolved oxygen has been employed as one criterion of water quality. The mathematical models developed in the present study can be directly applied to evaluation of dissolved oxygen profiles if the major sources of oxygen demand are included in the analysis. There are three (3) known major sources of dissolved oxygen demand. These are carbonaceous organic matter, nitrogenous oxygen demand, and the oxygen demand associated with bottom sediments.

To establish the relative significance of the several sources of oxygen demand, it is possible to consider the per-capita contributions. It is generally agreed that 0.17 pounds of five-day 20° BOD (1) is contributed per-capita. This is equivalent to approximately 0.265 pounds per day of ultimate oxygen demand. An acceptable daily per-capita nitrogen contribution (as N) is 0.022 pounds per day. Each pound of nitrogen requires in the order of 4.5 to 5.14 pounds of oxygen for oxidation to NO_3 and water. Thus the oxygen demand associated with carbonaceous BOD is 0.265 pounds per-capita per day, and the nitrogenous oxygen demand may be as high as 0.11 pounds per-capita per day. The ratio of nitrogenous oxygen demand to ultimate carbonaceous oxygen demand is in the order of 40 percent.

---

(1) Fair & Geyer, Water Supply and Waste-Water Disposal, John Wiley & Sons, Inc., 1954.

It is evident that data on the nitrogen content of wastes are required to realistically assess the oxygen demand of waste discharges. In this regard, it should be noted that with minor exceptions, even the waste input data available from treatment plants in the study area do not provide information which can be employed to evaluate the nitrogenous oxygen demand.

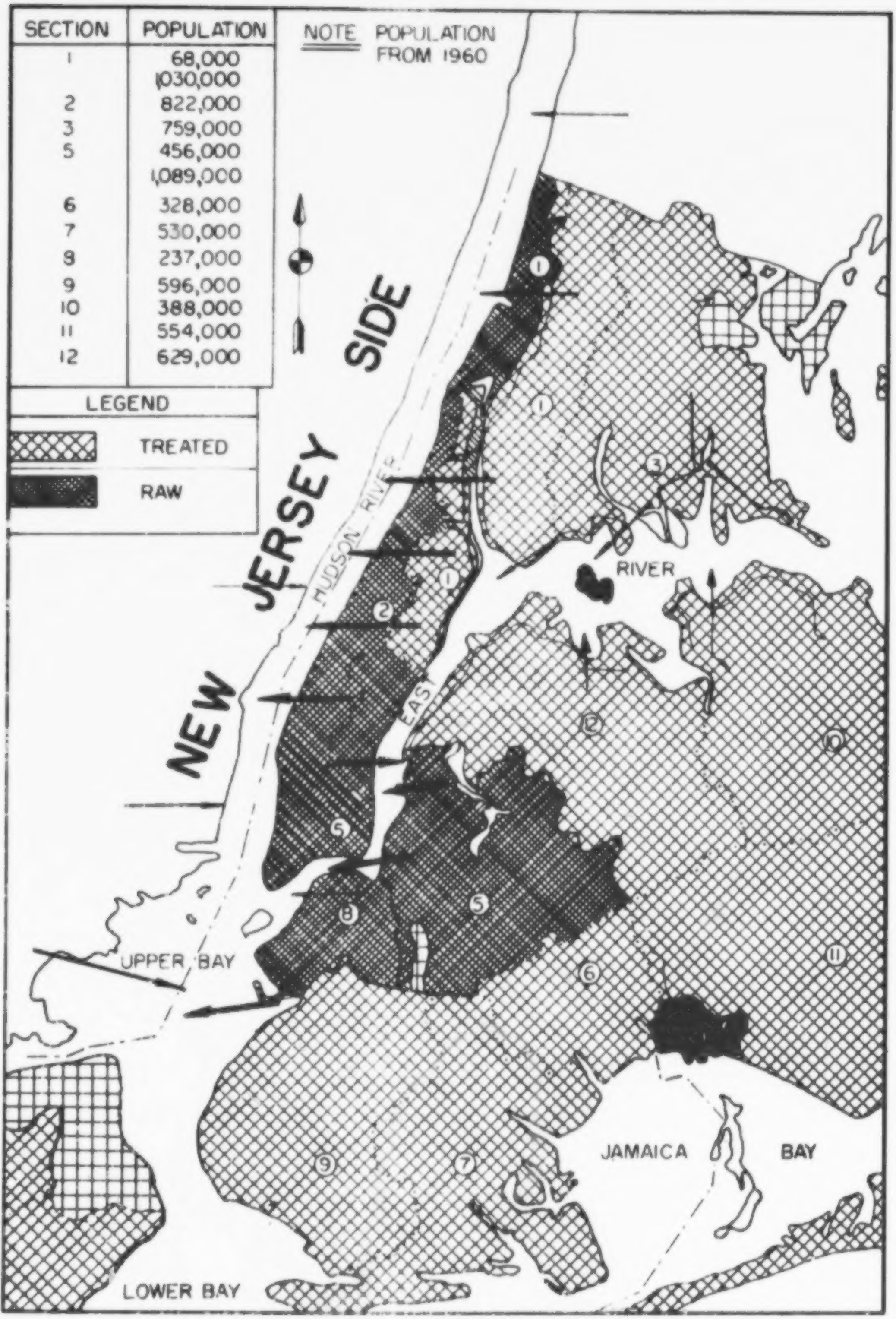
The location, mapping and evaluation of the oxygen demand associated with bottom sediments should be carried out in the study area. In this regard, it is possible to assess which specific regions of the study area would be significantly influenced by bottom oxygen demands. Water quality as measured by dissolved oxygen in areas with water depths in excess of thirty (30) feet are not likely to be significantly influenced by oxygen demand associated with bottom sediments. Sampling, mapping and measuring these areas could be delayed.

Experimental evaluation of loads to the system could be carried out by selecting specific raw waste discharges and obtaining measurements of flow, and other necessary parameters (including the nitrogen series.) The raw waste discharge could be the influent to a treatment plant or a raw discharge to the system. Efforts should be made to define the character of the contributing population. In particular, estimates of the relative contribution of the transient population and industrial discharge relative to the resident population are of particular significance in the New York Harbor complex. This experimental approach could be further applied to areas other than New York Harbor, if required.

In addition, it would be desirable to evaluate the nitrogenous oxygen demand associated with the effluents from the several types of treatment systems operated in the study area.

It is possible to approach the problem of evaluating waste inputs into the system by conducting a population study. Figure 23 presents an indication of the resident population in New York City for the census year 1960. Also indicated on this figure are load locations.

Table 24 was developed from a conversion of the resident population figures to pounds of ultimate BOD and total oxygen demand for each of the load locations indicated. An estimate of the industrial contribution and of the transient population must be added to the loading figures presented in the table. In this regard, one method of estimation of the transient population could be obtained by an analysis of the New York City income tax which collects revenue from transient non-resident workers in the city.


NOTE POPULATION FROM 1960
LEGEND
TREATED
RAW
NEW JERSEY SIDE
HUDSON RIVER
EAST RIVER
UPPER BAY
LOWER BAY
JAMAICA BAY
1
1
1
2
3
5
5
6
7
8
9
10
11
12

SECTION	POPULATION
1	68,000 1030,000
2	822,000
3	759,000
5	456,000 1,089,000
6	328,000
7	530,000
8	237,000
9	596,000
10	388,000
11	554,000
12	629,000

LEGEND	
▨	TREATED
■	RAW

FIGURE 23

TABLE 24a

1920

WASTE LOADS

Discharge Point	Population (resident)	Ultimate BOD pounds / day	Nitrogenous Demand (#/day)	Total Demand (pounds / day)	Equivalent 5 - day BOD
2A (1930)	169, 000	44, 800	18, 600	63, 400	42, 300
2B (1930)	169, 000	44, 800	18, 600	63, 400	42, 300
2C (1930)	169, 000	44, 800	18, 600	63, 400	42, 300
2D (1930)	169, 000	44, 800	18, 600	63, 400	42, 300
5B (1930)	535, 000	142, 000	58, 800	200, 800	134, 000
$5A_1$	328, 500	87, 100	36, 100	123, 200	82, 300
$5A_2$	328, 500	85, 100	36, 100	123, 200	82, 300
12A	106, 000	28, 100	11, 700	39, 800	26, 600
12B	106, 000	28, 100	11, 700	39, 800	26, 600
8	283, 000	75, 000	31, 100	106, 100	70, 700
9	374, 000	99, 200	41, 200	140, 400	93, 700

TABLE 24b

1950

WASTE LOADS

Discharge Point	Population (resident)	Ultimate BOD pounds / day	Nitrogenous Demand (#/ day)	Total Demand (pounds / day)	Equivalent 5-day BOD
2A	180, 000	47, 700	19, 800	67, 500	45, 000
2B	180, 000	47, 700	19, 800	67, 500	45, 000
2C	180, 000	47, 700	19, 800	67, 500	45, 000
2D	180, 000	47, 700	19, 800	67, 500	45, 000
5B	523, 000	138, 500	57, 500	196, 000	131, 000
$5A_1$	411, 500	109, 000	45, 200	154, 200	103, 000
$5A_2$	411, 500	109, 000	45, 200	154, 200	103, 000
12A	300, 000	79, 500	33, 000	112, 500	75, 000
12B	300, 000	79, 500	33, 000	112, 500	75, 000
8	300, 000	79, 500	33, 000	112, 500	75, 000
9	716, 000	190, 000	78, 700	268, 700	178, 500

TABLE 24c

1960

WASTE LOADS

Discharge Point	Population (resident)	Ultimate BOD pounds / day	Nitrogenous Demand (#/ day)	Total Demand (pounds / day)	Equivalent 5 - day BOD
2A	205, 500	54, 400	22, 600	77, 000	51, 400
2B	205, 500	54, 400	22, 600	77, 000	51, 400
2C	205, 500	54, 400	22, 600	77, 000	51, 400
2D	205, 500	54, 400	22, 600	77, 000	51, 400
5B	456, 000	121, 000	50, 100	171, 100	114, 000
$5A_1$	544, 500	144, 100	59, 800	203, 900	136, 000
$5A_2$	544, 500	144, 100	59, 800	203, 900	136, 000
12A	314, 500	83, 500	34, 600	118, 100	78, 600
12B	314, 500	83, 500	34, 600	118, 100	78, 600
8	237, 000	62, 800	26, 100	88, 900	59, 200
9	596, 000	158, 000	65, 500	223, 500	149, 000

The city of New York also has an industrial sewer charge ordinance. It would appear that the records of the City of New York on the number and character of industrial discharges within the system could be employed to provide an estimate of non-domestic waste contributions. The paper study to evaluate waste loads entering the New York Harbor complex is recognized as an approximation of the loads, but the results of a properly conducted study could provide the accuracy of information required for proper use of the mathematical model. The estimates of input waste quantities from a detailed study of an experimental or population nature would significantly improve the reliability of efforts to determine consistent sets of parameters for the waterways of the study area. It is therefore recommended that this very important phase of developing waste inputs be pursued as rapidly as practical. In the interim, the waste input location and magnitudes presented in this report can be employed to evaluate system parameters. Latitude to increase or decrease these inputs adds an undesirable yet realistic degree of freedom to the process of evaluating system parameters.

PRELIMINARY VALUES OF SYSTEM PARAMETERS

The mathematical models presented in this report require as input data the value of the several parameters of each segment of the system. Input also is required to define the physical, geophysical and hydraulic conditions.

The specific information required for each section of the water quality models are :

1. Waste discharge location.
2. Quantity of carbonaceous oxygen demand.
3. Quantity of nitrogenous oxygen demand.
4. Uniform waste loads (quantity and locations) .
5. Bottom oxygen demand (quantity and locations) .
6. Algae oxygen production and respiration rates and locations.
7. Cross-sectional area of the system as a function of distance. For constant area sections, the value of the cross-sectional area is required. For expanding area sections, the values of A_o and R_o are required.
8. The fresh water flow.
9. Dispersion coefficient " E " .
10. The reaeration coefficient " AK " .
11. BOD removal and BOD oxidation coefficients " RK " and " DK " respectively must be evaluated for the various types of waste inputs.

12. The physical length of the several sections and the region of application of the model.

13. The volume of completely mixed bodies.

Tables 25 to 27 present a summary of the available information on systems parameters and inputs defining geometry.

TABLE 25

NEW YORK HARBOR - PRELIMINARY VALUES OF PARAMETERS

Parameter and Units	Upper New York Bay	Lower East River	Upper East River	North River	Newark Bay	Lower Arthur Kill	Upper Arthur Kill	Kill Van Kull
Dispersion coefficient " E " (mi^2 / day)	24	10	10	20	10	10	10	10
BOD removal coefficient " RK " (1 / day)	0.25	0.25	0.25	0.25	0.26	0.25	0.25	0.25
BOD oxidation coefficient " DK " (1 / day)	0.25	0.25	0.25	0.25	0.26	0.25	0.25	0 .25
Reaeration coefficient " AK " (1 / day)	0.07	0.09	0.12	0.1	0.30	0.15	0.15	0.125
Cross-sectional area (ft^2)	340,000	80,000	$A_o = 80,000$	135,000	- -	35,000	$A_o = 24,250$	50,000
Area variation	None	None	$A = A_o\left(\frac{R}{R_o}\right)^2$	None	None	None	$A = A_o\left(\frac{R}{R_o}\right)^2$ R_o = 26 mi.	
Tidal Exchange (1 / day)	0.1 - 0.43	- -	- -	- -	0.1 - 0.3	- -	- -	- -
Volume ft^3	1.2×10^{10}	- -	- -	- -	1.2×10^9	- -	- -	- -

HUDSON ESTUARY
PRELIMINARY PARAMETER VALUES

Miles	Area (ft^2)	AK (1/day)	RK (1/day)	DK (1/day)	E (mi^2/day)	Ro (miles)	Area Variation
14	200,000	0.23	0.25	0.25	10[1]	- -	Constant
40	155,000	0.04	0.25	0.25	10[1]	- -	Constant
55	155,000	0.125	0.25	0.25	10[1]	- -	Constant
65	125,000	0.06	0.25	0.25	5[1]	- -	Constant
85	52,000[3]	0.15	0.25	0.25	5 to 1[1]	17.85[3]	$A\left(\frac{R}{Ro}\right)$
97	52,000[3]	0.275	0.25	0.25	5 to 1[1]	17.85[3]	
114	13,000[4]	0.165	0.25	0.25	1[2]	13.5[4]	$A\left(\frac{R}{Ro}\right)$
11	13,000[4]	0.125	0.25	0.25	1[2]	13.5[4]	
Troy Lock							

Notes:

1. " E " requires verification
2. " E " requires verification - profiles suggest low " E " values
3. Ro Located at 114 miles
4. Ro Located at Troy Lock

TABLE 27

RARITAN RIVER

Section No. 1

$X = 0$ to $X = 2.0$ miles : area = 450 ft^2

$E = 1.0$ $\text{miles}^2 / \text{day}$

$AK = 4.87$ 1 / day

$RK = DK = 0.25$ 1 / day

$P = 10$ mg / l / day

$R = 2.0$ mg / l / day

$F - 1.5$

Section No. 7

X 2.0 Ro_2 .55 miles limit HH = 9 miles

Section No. 2

Ro_2 .55 miles limit BB = 9 miles

NOTE: Solution must include a Section No. 7 and a Section No. 2. Therefore, for no load in this region, it is suggested that :

$Ro_2 = Ro_7 = .55$ miles

HH = 1.0 miles R at end of section No. 7 = 1.55 miles

$Ao_2 = Ao_7 = 450 \text{ ft}^2$

All parameters are equal →

$E = 5.0$

TABLE 27

(Continued)

AK = 0.80

RK = DK = 0.25

P = 10.0

R = 2.0

F = 1.5

Sections Nos. 3 and 4

$Ro_3 = Ro_2 + BB$ (in space)

Ro_3 = 1.77 miles

Ao_3 = 7970 ft^2

CC = 8.6 miles (limit)

EE = 8.6 miles (limit)

NOTE: Solution must include
Sections 3 and 4. Therefore,
for no load, it is suggested that:

CC = 1.0

EE = 8.6

All parameters are equal

E = 5.0

AK = .40

RK = DK = .25

P = 10

R = 2.0

F = 1.5

TABLE 27

(Continued)

Sections Nos. 5 and 6

Area = 2000 ft^2

X = O at Ro_3 at Ro_2 + BB

X = -5.8 miles limit

FF = -5.8 limit

DD = -5.8 limit

E = 5.0

AK = 0.43

RK = DK = 0.25

P = 10.0

R = 2.0

F = 1.5

USE FOR NO LOAD CONDITIONS :

FF = 2.6 miles

DD = -5.8 miles

NOTE : All distances, AA, HH, BB, CC, EE, FF, and DD are measured from origin of respective systems. That is, from :

AA from XR = O

HH and BB from Ro_2

CC and EE from Ro_3

FF and DD from XS = O

TABLE 27

(Continued)

NOTE: Flow over dam on Raritan is " Q " in Sections Nos. 1, 7, and 2. Flow over dam in South is " Q " in Sections 6. Section 5 has added flow at mile -2.6. Flow in Sections 3 and 4 equals sum of Flows in Sections 2+5.

AVAILABLE DATA ON WATER QUALITY AND SYSTEM INPUTS

Relatively extensive data and information on water quality are available for the major waterways in the study area. The vast majority of water quality data in the study area was not obtained with a view towards use in evaluating water quality in the subject waterways as a factor which results from system characteristics and waste inputs. The available information has been averaged on a monthly basis and is considered to represent mean tidal water quality. This procedure is necessary since the data is not obtained with respect to a known or fixed point in the tidal cycle. The majority of available data provides at least some water quality information for particular points in space and time. In view of the above, the bulk of water quality data available for the system can be used as a preliminary basis of comparison with the mathematical models developed in this work.

The New York Harbor complex is sampled regularly by the New York Department of Public Works. The location of specific sampling stations used by the Department are shown on Figure 24. Surface and bottom samples are collected and analyzed for temperature, dissolved oxygen, chlorides, biochemical oxygen demand, and coliform bacteria. Samples are obtained on a regular basis once or twice a week during the period from June to September of each year.

The data thus collected is representative of water quality

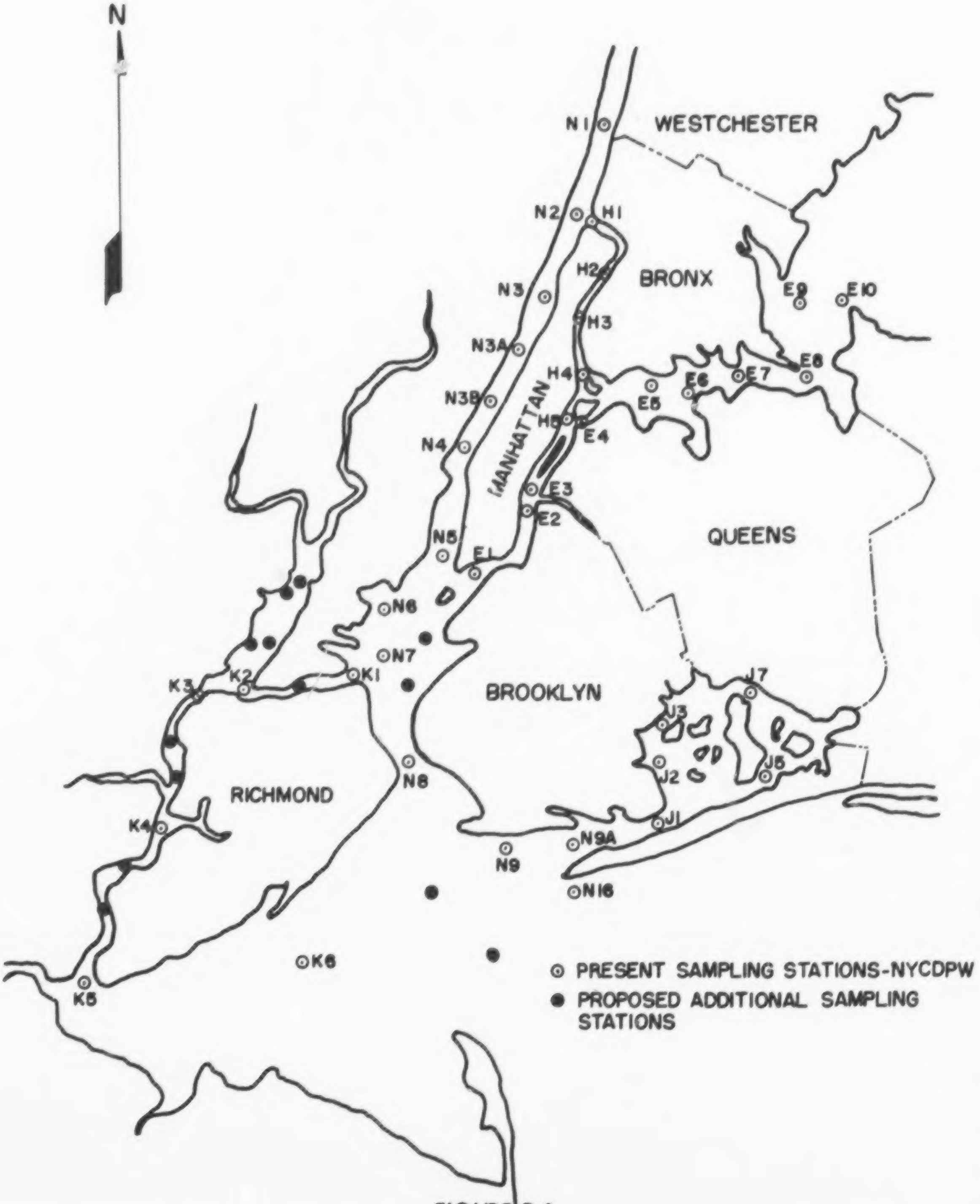

N
WESTCHESTER
BRONX
MANHATTAN
QUEENS
BROOKLYN
RICHMOND
N1
N2
H1
H2
N3
H3
N3A
H4
N3B
H5
E4
N4
E3
E2
N5
E1
N6
N7
K1
K2
K3
K4
K5
K6
N8
N9
N9A
N16
J1
J2
J3
J5
J7
E5
E6
E7
E8
E9
E10
⊙ PRESENT SAMPLING STATIONS-NYCDPW
● PROPOSED ADDITIONAL SAMPLING STATIONS

FIGURE 24

PROPOSED SAMPLING STATIONS FOR METROPOLITAN NEW YORK HARBOR COMPLEX at the location sampled for the particular point in the tidal cycle present at the station at the time the sample was obtained. Figures 25 and 26 are presented for two East River stations and for different sampling years. The variation in the observed data for chlorides, and dissolved oxygen are in large part a result of sampling the same location at differing points in the tidal cycle. The biochemical oxygen demand concentration profile in the East River is relatively uniform. Thus, as would be anticipated, data obtained at a fixed location for varying points in the tidal cycle would appear to be uniform, and relatively insensitive to tidal translation. The same reasoning on uniformity may be applied to the water temperature data. In the case of temperature, one observes from Figures 25 and 26 that the temperature at a station varies significantly during the months sampled.

Two basic requirements for comparison of water quality data with calculated profiles from the mathematical models are :

1. The data from the various stations must represent water quality at those stations for the same instant in time and point of the tidal cycle. The point in the tidal cycle must be known.
2. The system must be at or near steady-state conditions with respect to those

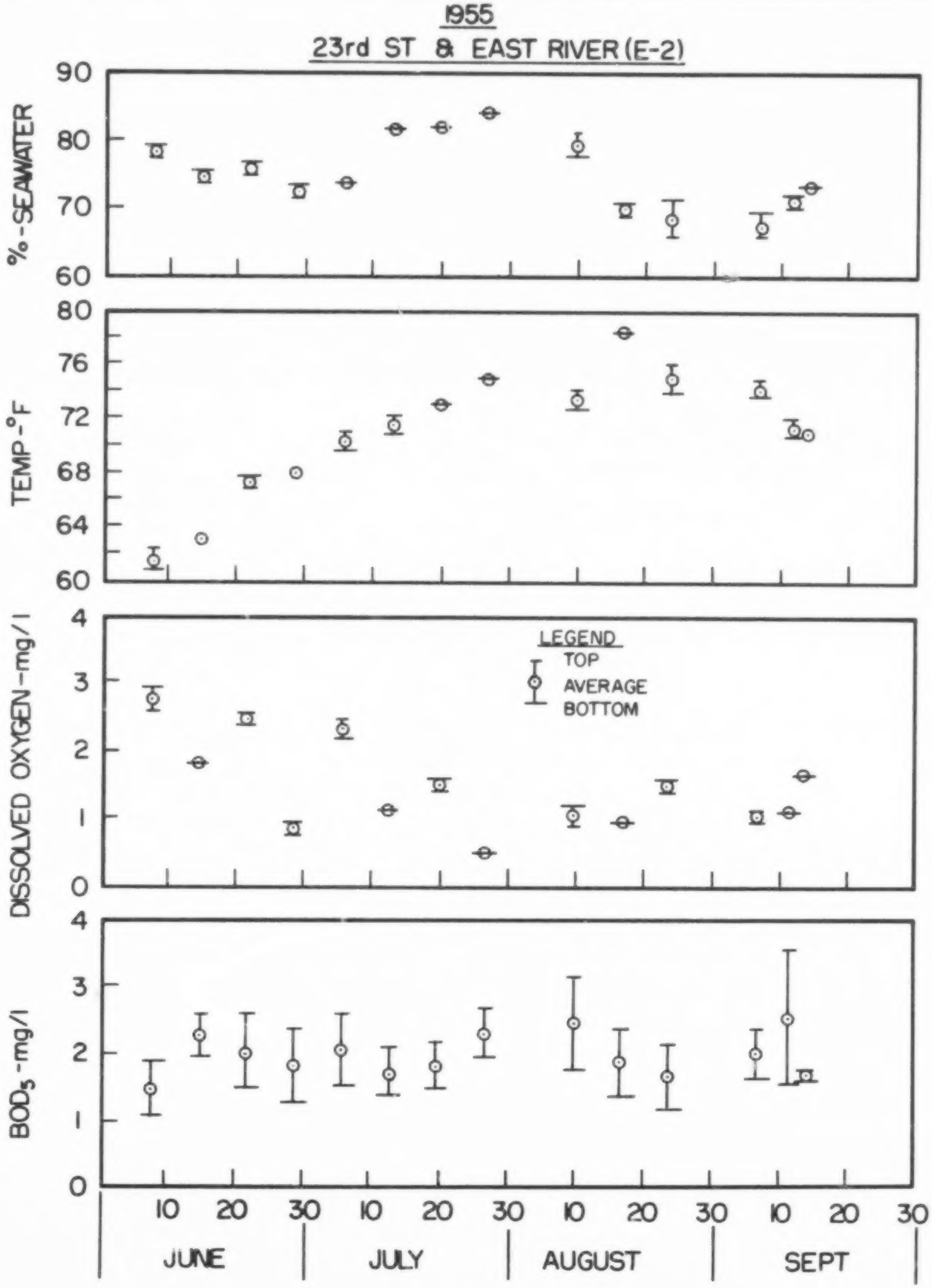

1955
23rd ST & EAST RIVER (E-2)
%-SEAWATER
90
80
70
60
TEMP-°F
80
76
72
68
64
60
DISSOLVED OXYGEN-mg/l
4
3
2
1
0
LEGEND
TOP
AVERAGE
BOTTOM
BOD5-mg/l
4
3
2
1
0
10
20
30
10
20
30
10
20
30
10
20
30
JUNE
JULY
AUGUST
SEPT

FIGURE 25

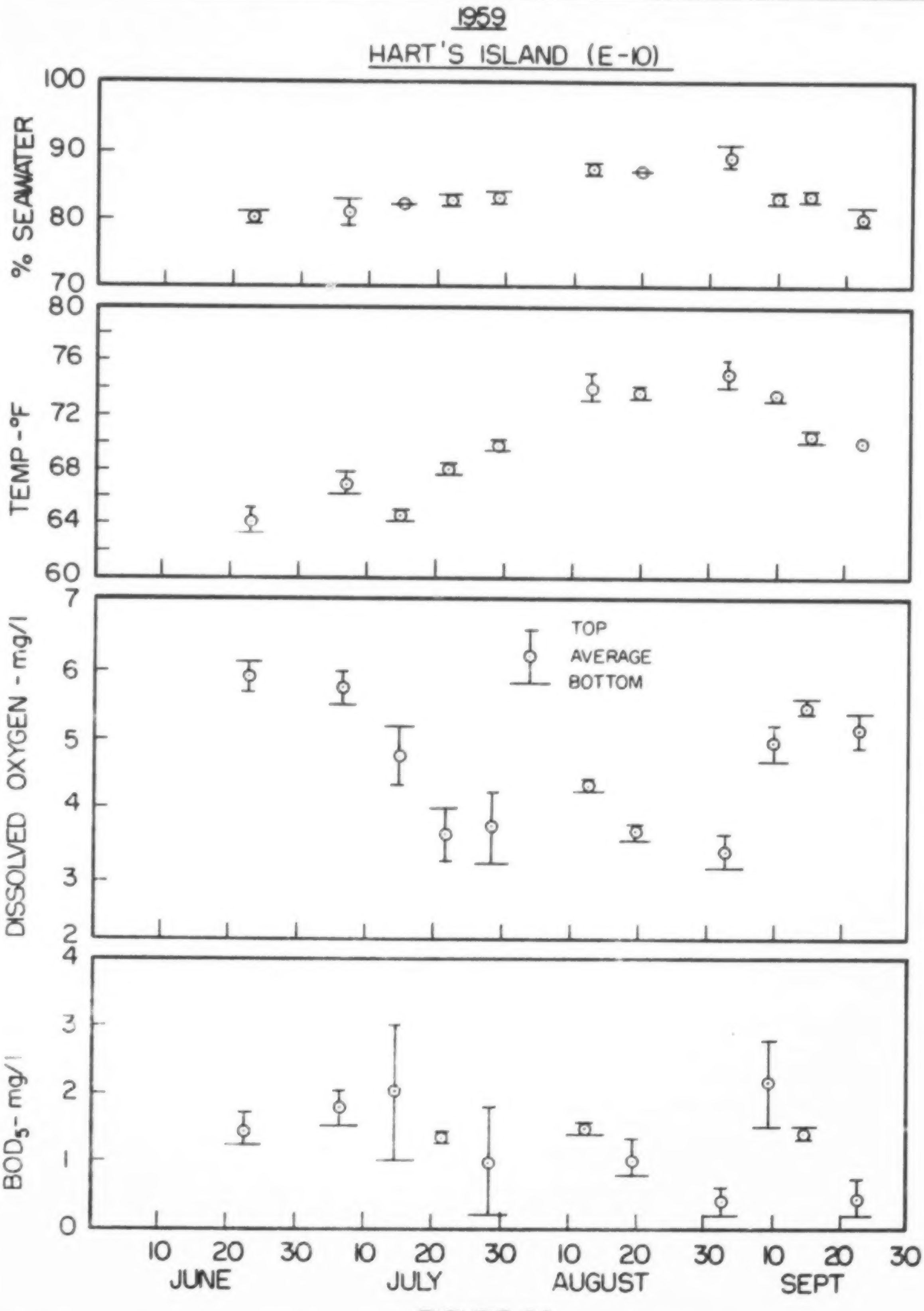

1959
HART'S ISLAND (E-10)
% SEAWATER
100
90
80
70
TEMP - °F
80
76
72
68
64
60
DISSOLVED OXYGEN - mg/l
7
6
5
4
3
2
TOP
AVERAGE
BOTTOM
BOD$_5$ - mg/l
4
3
2
1
0
10
20
30
10
20
30
10
20
30
10
20
30
JUNE
JULY
AUGUST
SEPT

FIGURE 26

factors which influence water quality. In New York Harbor, the primary time variable factors which influence water quality are flow and water temperature. In the general case waste discharges, algae, and nitrogenous oxidation, may be added to the list of possible time varying phenomena.

A review of the water temperature data on Figures 25 and 26 indicates that steady-state temperature conditions are probably approached during the months of July and August. A convenient period for grouping New York City Department of Public Works water quality data is on a monthly basis. This method was selected for the present analysis, and is recommended for handling this type of data.

One of the major tasks which the sponsors of this study, The Federal Water Pollution Control Adminstration, have retained in contracting for the present developments is the manipulation of the water quality models to develop a set of consistent parameters which when used in the mathematical models will reproduce observed water quality profiles. To facilitate these activities, the New York City Department of Public Works data has been averaged by period for a number of years. The averages are tabulated and presented in the appendix of this report. Additional sources of data on water quality in the New York Harbor complex are from the Interstate Sanitation Commission, and the Federal Water Pollution Control Administration's own data.

Water quality information on the areas outside the New York Harbor area are more limited in quantity, but generally were obtained on a random basis insofar as the tidal cycle is concerned. Various sets of observed water quality data are presented as part of this report to illustrate the method of utilizing water quality models and evaluating the required parameters. Since the purpose of the report was to develop mathematical models of the area, no effort has been made to tabulate all the available water quality data in the study area.

SENSITIVITY

System sensitivity may be defined as the relative change in water quality associated with changes in the parameters or the geometry of the system. There are three (3) significant areas where system sensitivity has a bearing on the use and application of mathematical models for water quality.

In the first instance, the relative sensitivity of the system to changes in the value of a parameter can be employed to determine the accuracy with which this parameter should be measured. The accuracy with which a parameter should be measured will in turn dictate the amount of money and effort to be spent in conducting field tests. As an example, a system may be relatively insensitive to fresh water flow and dispersion. Efforts to develop refined estimates of these parameters can be minimized. If, on the other hand, the system is sensitive to the nature and magnitude of waste inputs and to the value of the reaeration coefficient, expenditures to develop realistic and well-defined estimates of these parameters and inputs are justified. In summary, information on the value of all system parameters, inputs and geometry are required. Expenditures for developing highly refined estimates of the various items should be viewed in terms of their influence on the water quality profiles; that is, the systems' sensitivity.

A second area where knowledge of the system sensitivity is important is in developing a realistic set of consistent parameter values. It is necessary to obtain calculated water quality profiles which are in agreement with observed data in order to validate the model. Knowledge of the influence of changes in parameters on calculated profiles will assist in establishing the direction and magnitude of changes in the assigned value of parameters and inputs. This will speed up the process of determining a consistent set of parameters which will provide agreement between calculated and observed profiles at various temperature and flow conditions.

The third area where knowledge of system sensitivity is significant is in selection and evaluation of the methods for improving water quality. As an example, if water quality is insensitive to changes in fresh water flow, this would indicate that low flow augmentation may not be a realistic method of improving water quality. On the other hand, the system may be sensitive to tidal exchange and changes in system volume. This indicates that consideration should be given to methods of increasing tidal exchange and increasing the system volume as a means of improving water quality.

It should be noted that the sensitivity of the system to a change in the value of a single parameter will vary depending on the specific value of all parameters; several general indications of system sensitivity can be defined. These are:

1. The linear nature of the mathematical models results in changes in the calculated BOD and dissolved oxygen deficit profiles in direct proportion to changes in waste inputs. That is, a 10 percent reduction in a waste discharge load will result in a 10 percent reduction in the calculated BOD and dissolved oxygen deficit profiles associated with the load.

2. Steep concentration gradients will tend to be destroyed by relatively small increases in the value of the dispersion coefficient. It should be noted that the influence of changes in the dispersion coefficient " E " are reduced when relatively flat profiles (low concentration gradients) are present.

3. The net influence on water quality resulting from changes in the value

of specific parameters will vary
depending upon the location of
the point in the system being considered.

To illustrate this point, Figures 27 to 31 are presented. The Figures contain plots of a plane formed by the variable fresh water velocity " U ", the dispersion coefficient " E ", and the calculated dissolved oxygen deficit, " D ". The values of RK and AK are constant and each Figure illustrates the variation of the calculated dissolved oxygen deficit at a specific location for various combinations of values of " U " and " E ". In Figures 27 to 31, for locations upstream of the point of the waste discharge, one notes that the maximum deficit always occurs at low values of " U " and " E ". The shape and magnitude of the changes in curvature of the planes describe the influence of changing the parameters " U " and " E ". Figures 27 to 31 are the comparable planes for locations downstream from the point of waste introduction. It will be noted from these Figures that for a constant value of the dispersion coefficient, " E ", the fresh water velocity " U " at which the maximum deficit occurs increases as the location studied becomes more remote from the waste input location. That is, at a station located 10 miles from the point of waste introduction, the dissolved oxygen deficit increases as the fresh water velocity increases, with the maximum deficit occurring at the station when the flow velocity is in the order of

SENSITIVITY PLANES

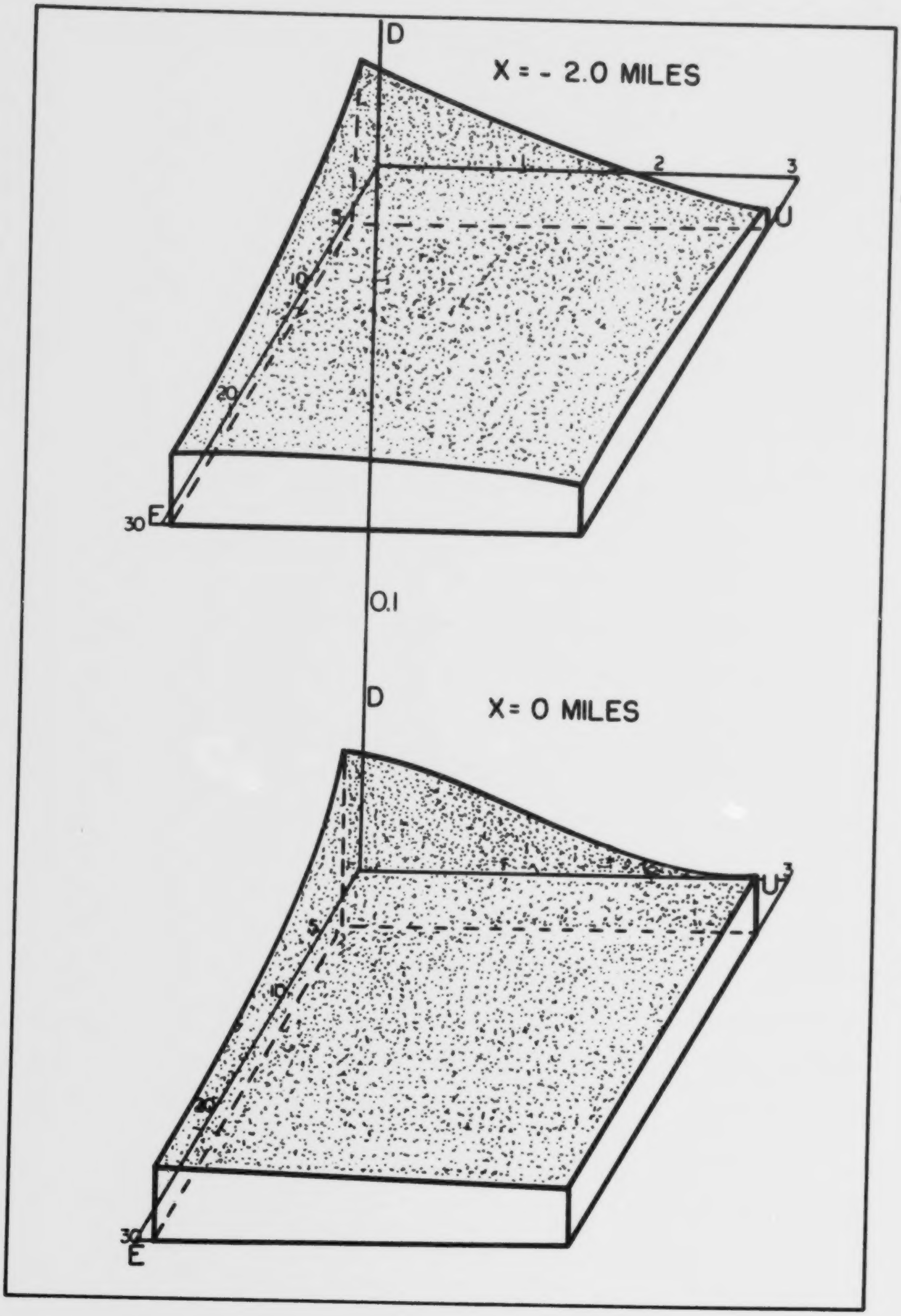

D
X = - 2.0 MILES
1
2
3
U
5
10
20
30
E
0.1
D
X = 0 MILES
3
U
5
10
20
30
E

FIGURE 27

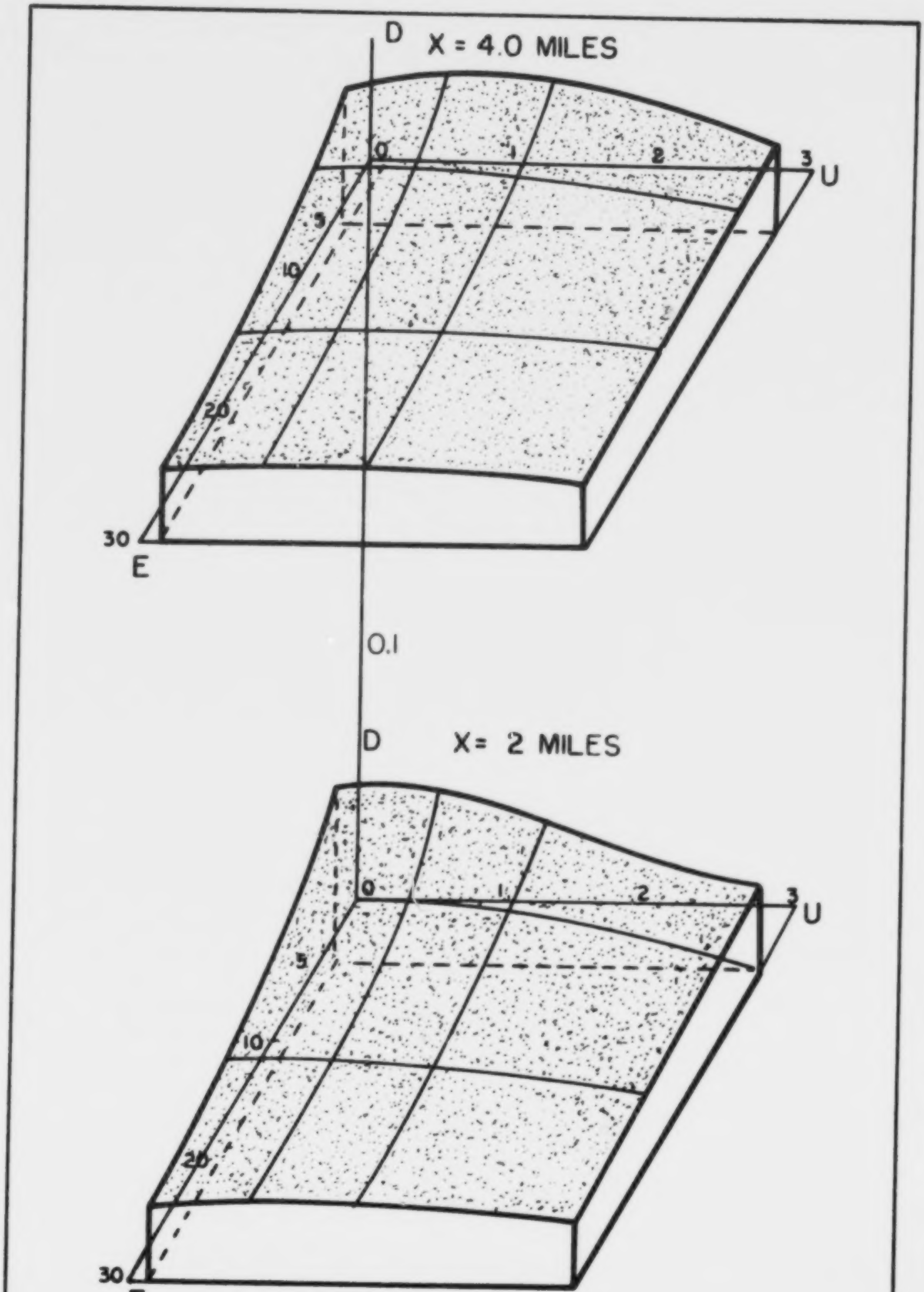

D
X = 4.0 MILES
0
1
2
3
U
5
10
20
30
E
0.1
D
X = 2 MILES
0
1
2
3
U
5
10
20
30
E

FIGURE 28

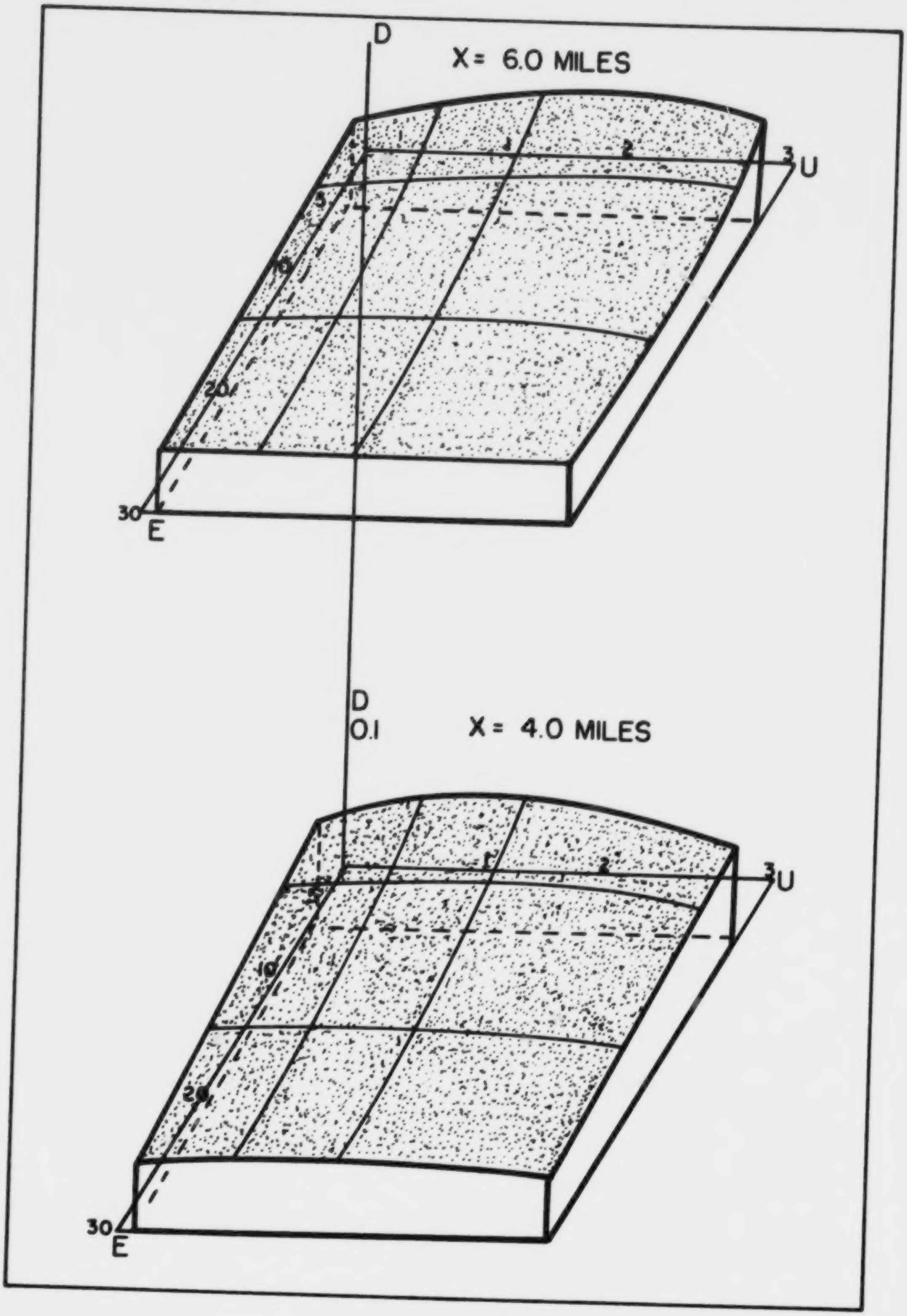

D
X = 6.0 MILES
1
2
3
U
5
10
20
30
E
D
0.1
X = 4.0 MILES
1
2
3
U
5
10
20
30
E

FIGURE 29

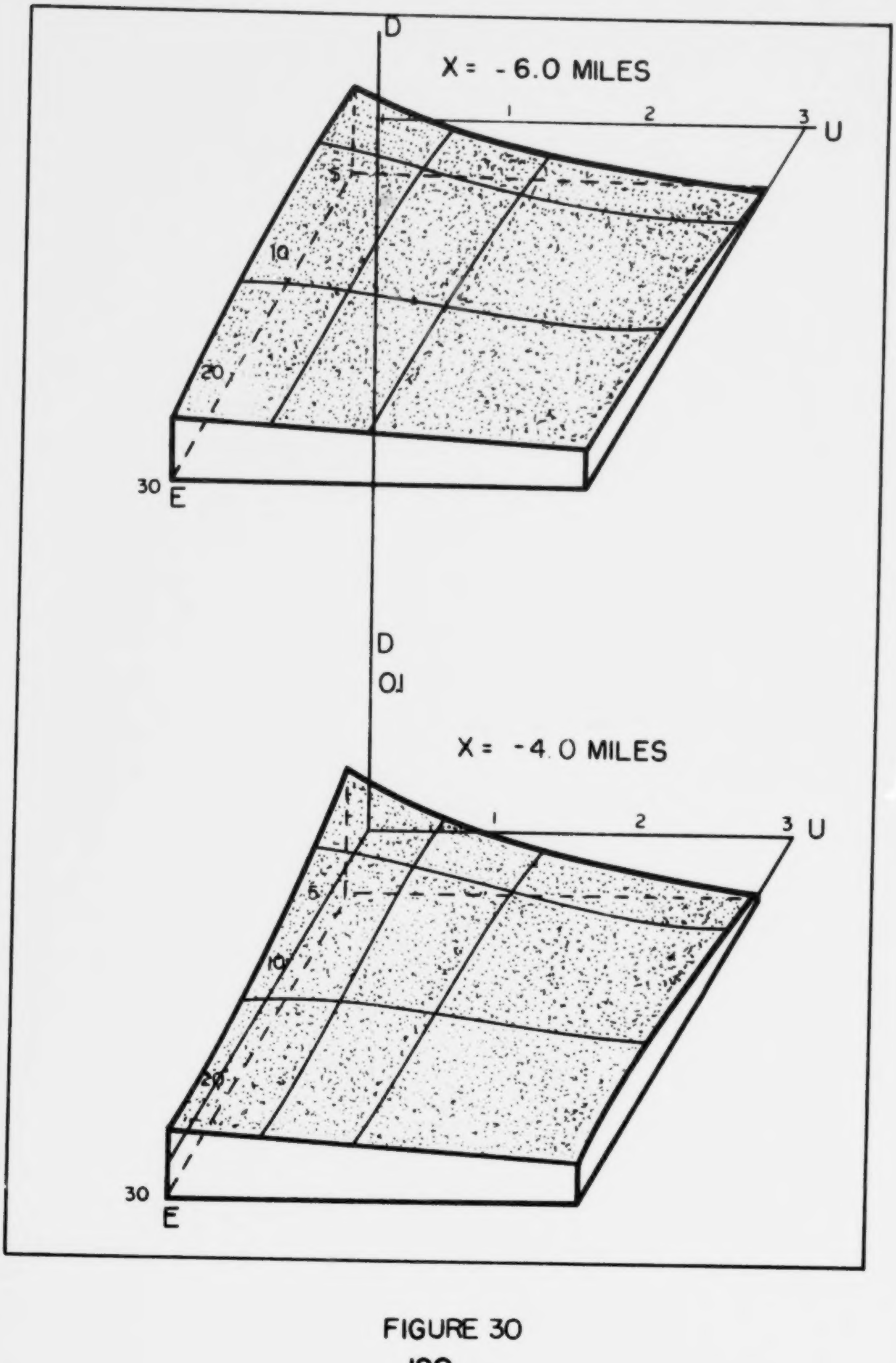

D
X = -6.0 MILES
1
2
3
U
5
10
20
30
E
D
X = -4.0 MILES
1
2
3
U
5
10
20
30
E

FIGURE 30

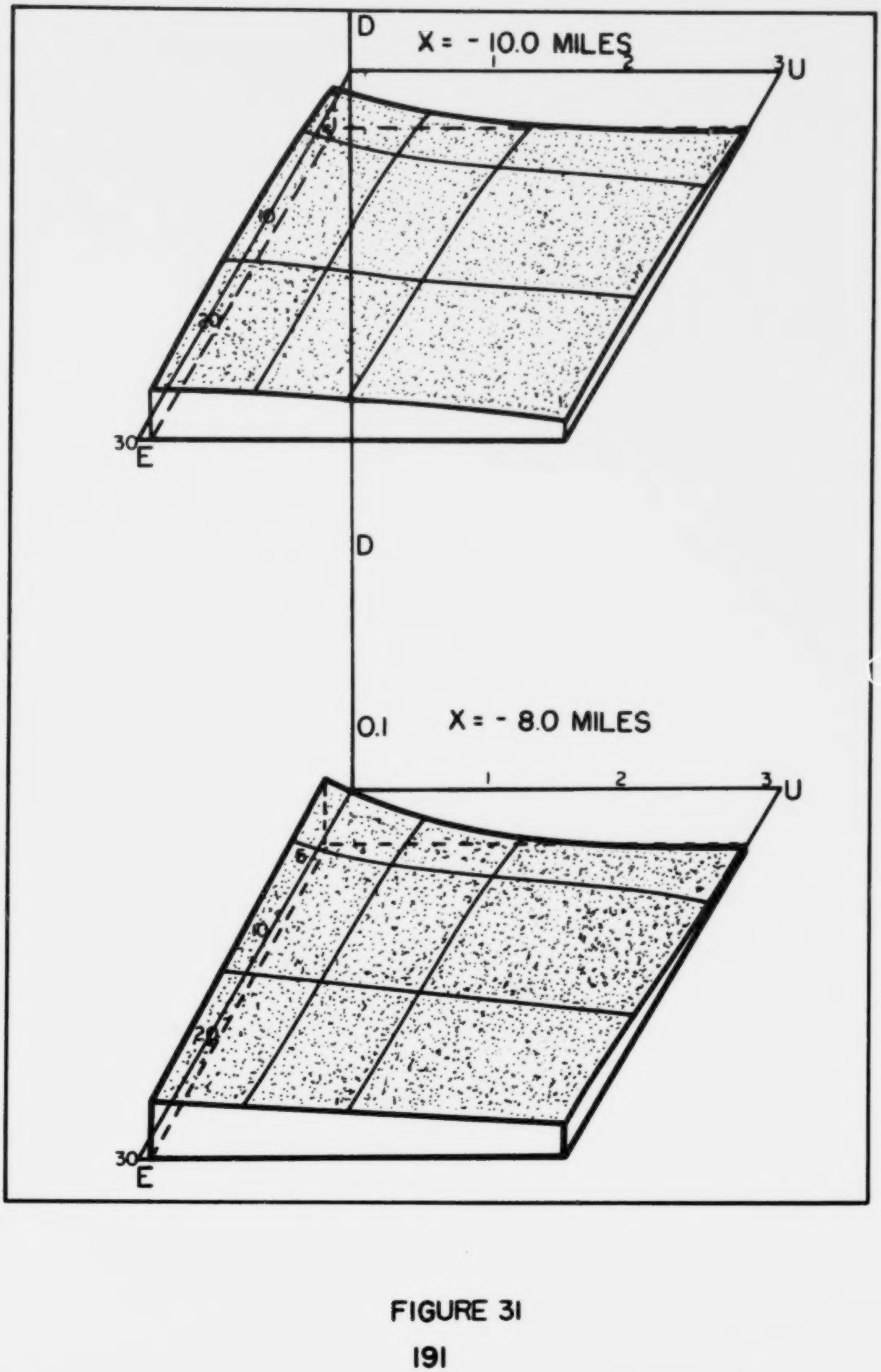


FIGURE 31

two (2) miles per day.

The specific planes presented in this report were developed from consideration of an infinite estuary. The geometry of the estuary may have significant effects on the shape of the planes and in general, on the sensitivity and behavior of the system.

An example of the influence of geometry on system sensitivity and behavior is illustrated in Figures 32 and 33 . In these Figures, a four (4) section system is considered with no fresh water flow. In Figure 32 , the point of waste introduction is located between the two middle sections at X = O. Case #1 on this Figure illustrates the calculated dissolved oxygen deficit curve when each of the four sections has the same cross-sectional area. In Case #2 of this Figure, the cross-sectional area of the extreme section has been increased by a factor of four (4). It can be observed that for Case #2, the entire deficit profile is significantly reduced in magnitude and the maximum deficit occurs behind the point of waste introduction, and away from the section with the large cross-sectional area. Figure 33 presents profiles for comparable system geometries. In this instance, the waste input location is bounded by an infinity section. It should be noted that for Case #1, in both Figures 32 and 33 when the estuary geometry is comparable in all sections, the location of the waste input does not influence the magnitude of the maximum deficit, which is 5 ppm and occurs at the point of waste input. In Case #2 for both Figures 32 and 33 , the maximum deficit occurs behind the waste input, away

ZERO FLOW ANALYSIS

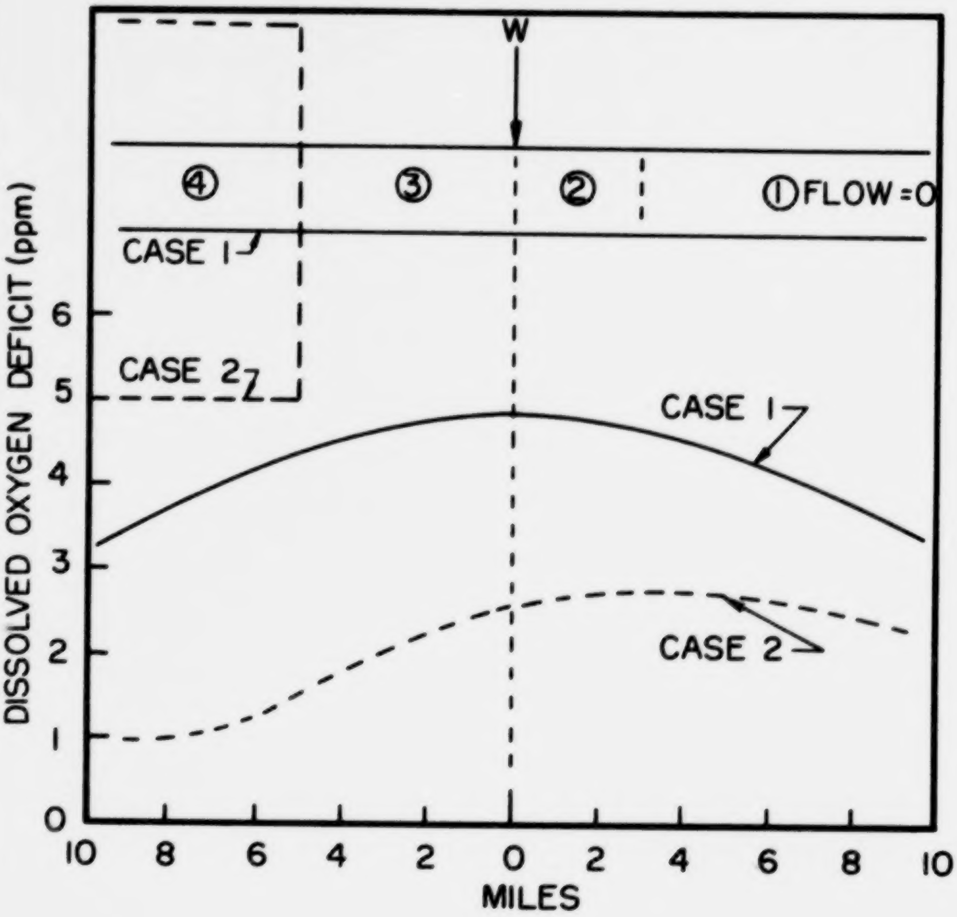


FIGURE 32

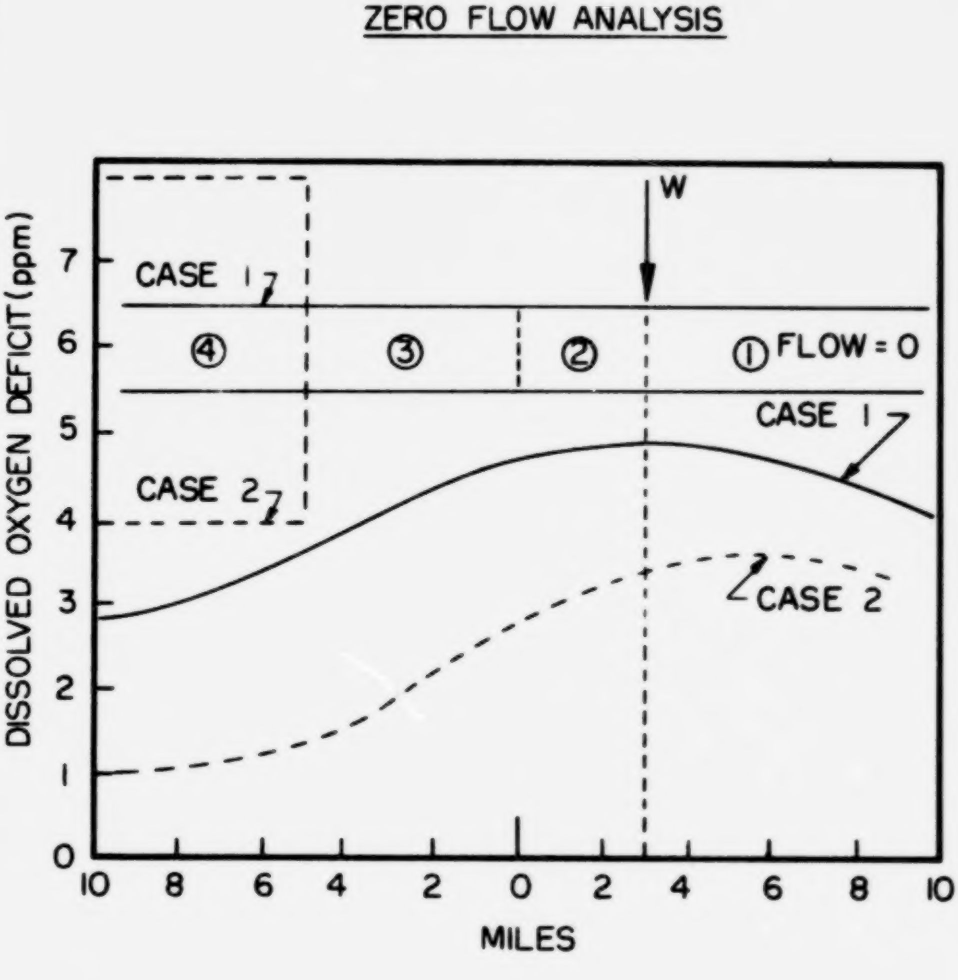

ZERO FLOW ANALYSIS
W
CASE 1
④
③
②
① FLOW = 0
CASE 1
CASE 2
CASE 2
DISSOLVED OXYGEN DEFICIT (ppm)
0
1
2
3
4
5
6
7
10
8
6
4
2
0
2
4
6
8
10
MILES

FIGURE 33

from the section with the large cross-sectional area. Note that the magnitude of the maximum deficit is lower in Case #2, as the waste load location approaches the section with the large cross-sectional area.

Several points of information on sensitivity can be made from an analysis of the information presented in Figures 32 and 33 .

1. The maximum dissolved oxygen deficit occurs at the point of waste discharge for symetrical systems with zero fresh water flow .
2. The maximum deficit need not occur at the point of waste discharge for unsymmetrical systems with zero flow.
3. The calculated dissolved oxygen deficit from a constant waste input decreases as the liquid volume of the system increases.

Figure 34 presents a plot of the plane relating the deficit to the deoxygenation " DK " and reaeration " AK " coefficient. Note the marked reduction in deficit associated with increasing reaeration coefficient. L'Hospital's rule is applicable to the range where AK = RK as the particular integral in the deficit solution contains the difference in the two coefficients (DK/AK-RK) . The increase in deficit due to an increase in the deoxygenation coefficient is also

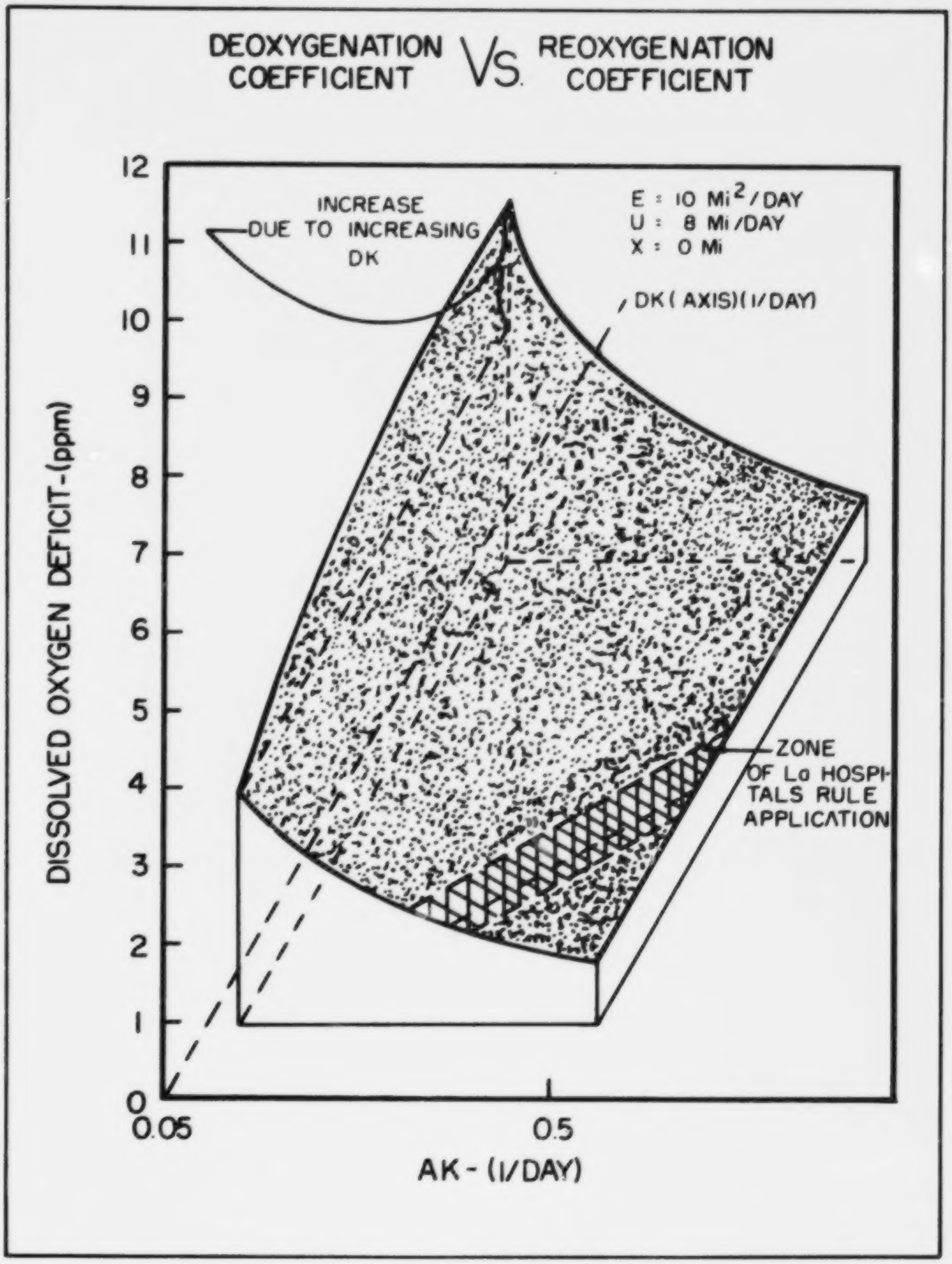

DEOXYGENATION COEFFICIENT VS. REOXYGENATION COEFFICIENT
INCREASE DUE TO INCREASING DK
E : 10 Mi² / DAY
U : 8 Mi / DAY
X : 0 Mi
DK (AXIS)(1/DAY)
ZONE OF La HOSPITALS RULE APPLICATION
DISSOLVED OXYGEN DEFICIT-(ppm)
12
11
10
9
8
7
6
5
4
3
2
1
0
0.05
0.5
AK - (1/DAY)

FIGURE 34

indicated on the Figure. The range of the deoxygenation coefficient DK on Figure 34 is from 0.05 to 0.5 per day.

The deficit calculations in Figure 35 were obtained employing the East River section of the North River model. In this model, the North River and upper Harbor are considered flowing bodies. Tidal exchange may be included in this type of model by considering the BOD removal and the reaeration coefficient as composed of the respective coefficients plus the exchange coefficient:

$$RK = RK + R$$

$$AK = AK + R$$

In the particular example illustrated in Figure 35 , $R = 0.43$ per day. The influence of tidal exchange may be observed to reduce the calculated deficit by as much as 0.3 ppm in 0.5 ppm at the junction of the East River and Harbor. The influence of tidal exchange is reflected in the dissolved oxygen deficit curves, 18 miles above the location of the section where tidal exchange has been added. This points out one of the basic properties of the dispersive phenomena in estuaries as defined by the dispersion coefficient, " E ". In the present example " E " was equal to 10.

The previous discussions have indicated, in a limited manner, the response of estuary systems to changes in parameters, inputs and geometry. The area of system sensitivity is relatively complex and requires additional effort before adequate definitions are available to define the anticipated behav-

INFLUENCE OF TIDAL EXCHANGE ON CALCULATED PROFILES OF DEFICIT

FLOW = ZERO
NORTH RIVER MODEL EAST RIVER SECTION

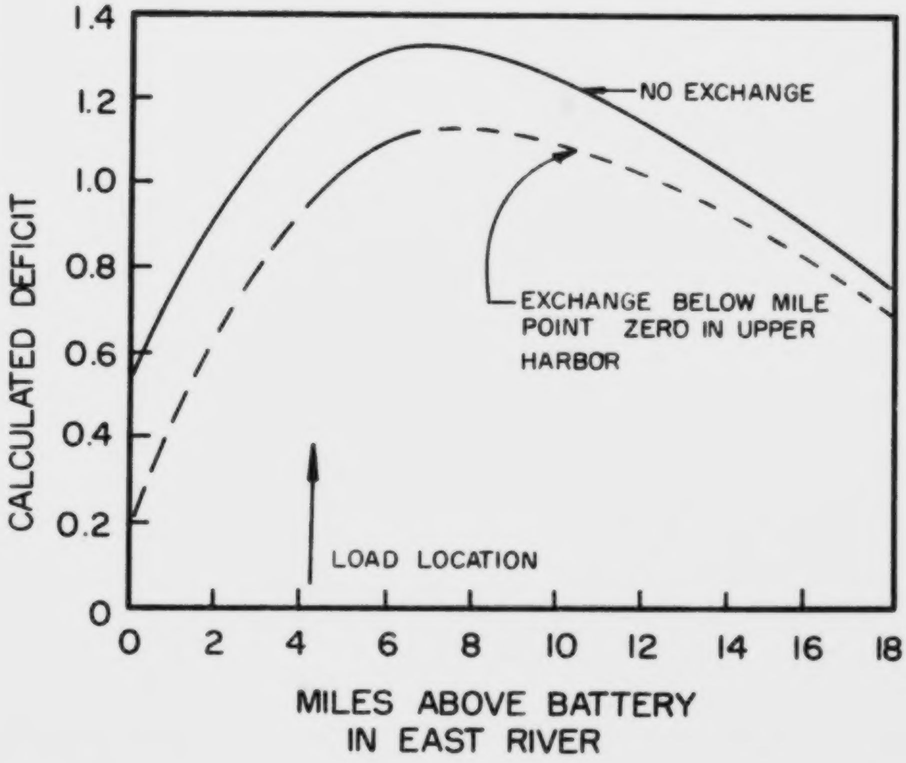


FIGURE 35

ior of the waterways which are being studied in the present program.

It is suggested that as part of the analysis and use of the mathematical models for water quality a systemic effort be made to develop an understanding of the behavior and sensitivity of the system. Specifically, it is suggested that for each of the models the following program be developed:

1. Obtain first, best estimates of all system parameters, inputs and geometry.
2. Using a unit load in all sections, develop profiles employing the best estimates obtained in No. 1 above.
3. Repeat the procedure in item No. 2 for ranges of all the system parameters. The best estimates may initially be halved and doubled. (As an example, E = 10 best estimate, also evaluate E = 20 and E = 5.)

A major challange remains in developing a convenient graphical method of presenting and displaying this information on system behavior and sensitivity. This report has employed individual profiles and three-dimensional graphs. In all cases, room for improvement in techniques for displaying system sensitivity remain. The program for evaluating system sensitivity should include provisions to provide information in all three of the significant areas of application. Namely:

1. Determination of the variables and parameters which require refined field measurements because the system is sensitive to these items. This will provide information on what must be measured, and the required accuracy.
2. Determination of changes in calculated profiles to assist in developing a consistent set of parameters defining all of the phenomena having a major influence on water quality.
3. Determination of the feasibility of alternate methods of improving water quality based upon the systems' response to changes in parameters, inputs, and geometry.

DISCUSSION

This report has presented a method of developing mathematical models for water quality which can be employed to assess the effectiveness of treatment and other alternative methods of improving water quality.

The model techniques presented in the section of this report entitled "Method for Evaluation and Presentation of Boundary Conditions for Complex Estuaries" can be utilized to evaluate water quality in the entire system understudy and can provide the models for all the smaller components of the system. The capability of the techniques presented is broad. The computer program which should be an outgrowth of the technique can replace all programs which were aimed at providing models for each of the smaller component waterways. It is suggested that the program utilizing the complex estuary technique be used in preference to the smaller programs for the system under study. This approach will allow for consideration of various combinations of loading and segmentation, regardless of the system being studies. In addition, excercise of the more general program will enable the users to become familiar with the capability of the technique.

Mathematical models for water quality provide a necessary tool for developing a coherent and consistent plan for water quality improvement. The models can also supply a needed input into an optimization program which can consider alternative methods of achieving several water quality goals. The model, however, is basically a response function for the system. The effectiveness and accuracy of predictive exercises employing this tool are directly influenced by the degree of verification of the model. The verification sequence essentially consists of evaluation of parameters through comparison of observed and calculated water quality profiles. The comparison results in the isolation of areas of unknown which can often be evaluated through field and or laboratory study. A comparison of observed and calculated profiles are obtained employing the additional information. This can result in the subsequent isolation of additional areas requiring definition. The procedure is repeated, exercising the model, developing comparisons of observed and calculated profiles, and returning to the field to collect additional data required to strengthen the analysis. It is highly desirable to have the interplay between a field program and model verification to strengthen the analysis.

A North River model was employed as an illustration of the comparison between calculated and observed oxygen deficit profiles for the Hudson River and upper New York Harbor. Figure 7 is a schematic diagram of the North River system and Table 19 contains a listing of estimates of input loads used.

The specific values of the various parameters are indicated in the section of the report on preliminary values of parameters. Figures 36 to 38 present the calculated cumulative dissolved oxygen deficit profiles for three flow and temperature conditions. The observed data for the flow and temperature conditions are also presented on the figures. There is reasonably good agreement between observed and calculated profiles in the Hudson River and upper New York Harbor. Figures 39 to 41 present the calculated dissolved oxygen deficit profiles and observed data in the East River for the same periods. The North River model was employed in these calculations and the profiles presented indicate the effect of all loadings in the model on the East River. Reasonably good agreement is obtained between observed and calculated information. It should be noted, however, that the expanding area portion of the East River is not

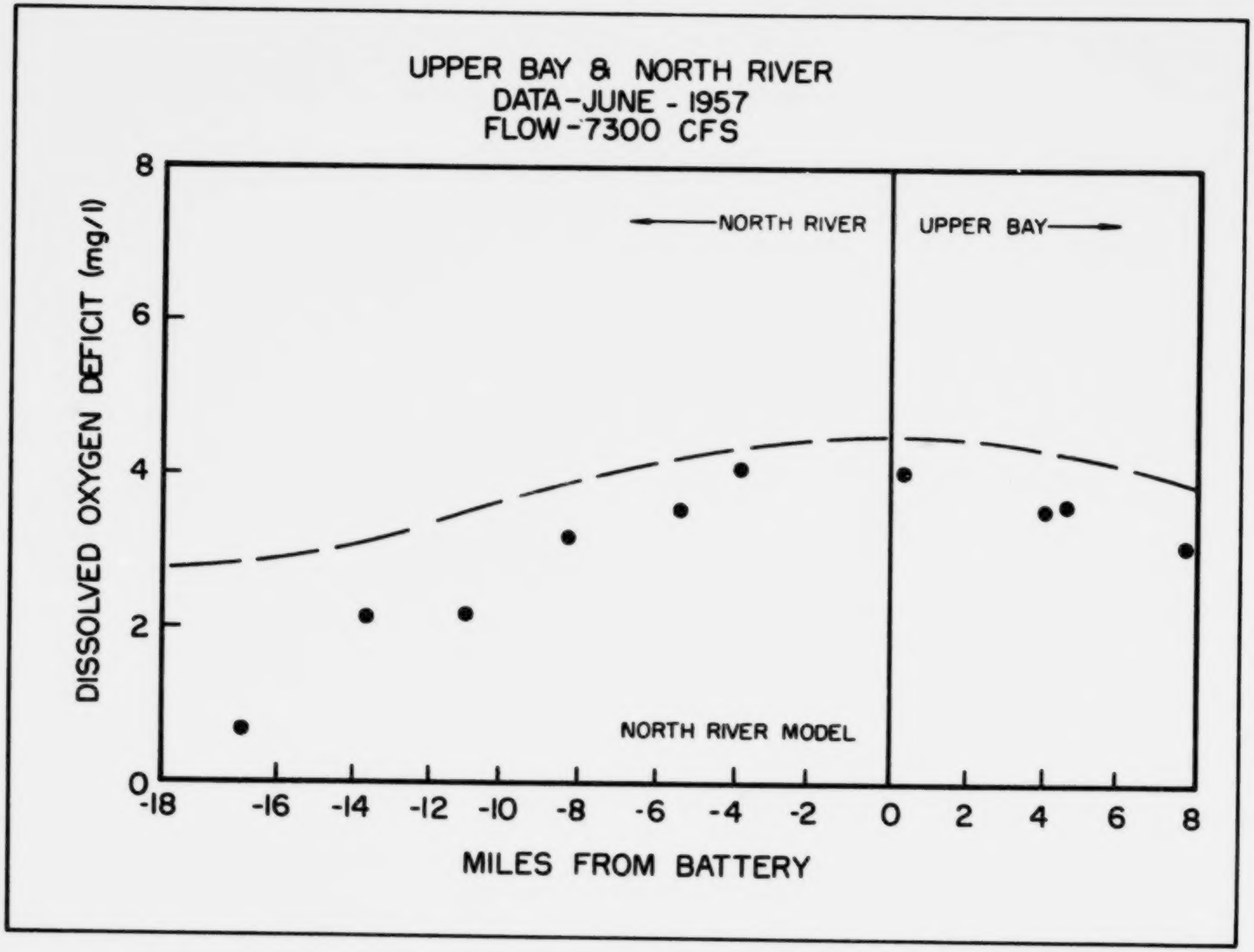

UPPER BAY & NORTH RIVER
DATA-JUNE-1957
FLOW-7300 CFS
DISSOLVED OXYGEN DEFICIT (mg/l)
8
6
4
2
0
NORTH RIVER
UPPER BAY
NORTH RIVER MODEL
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
MILES FROM BATTERY

FIGURE 36

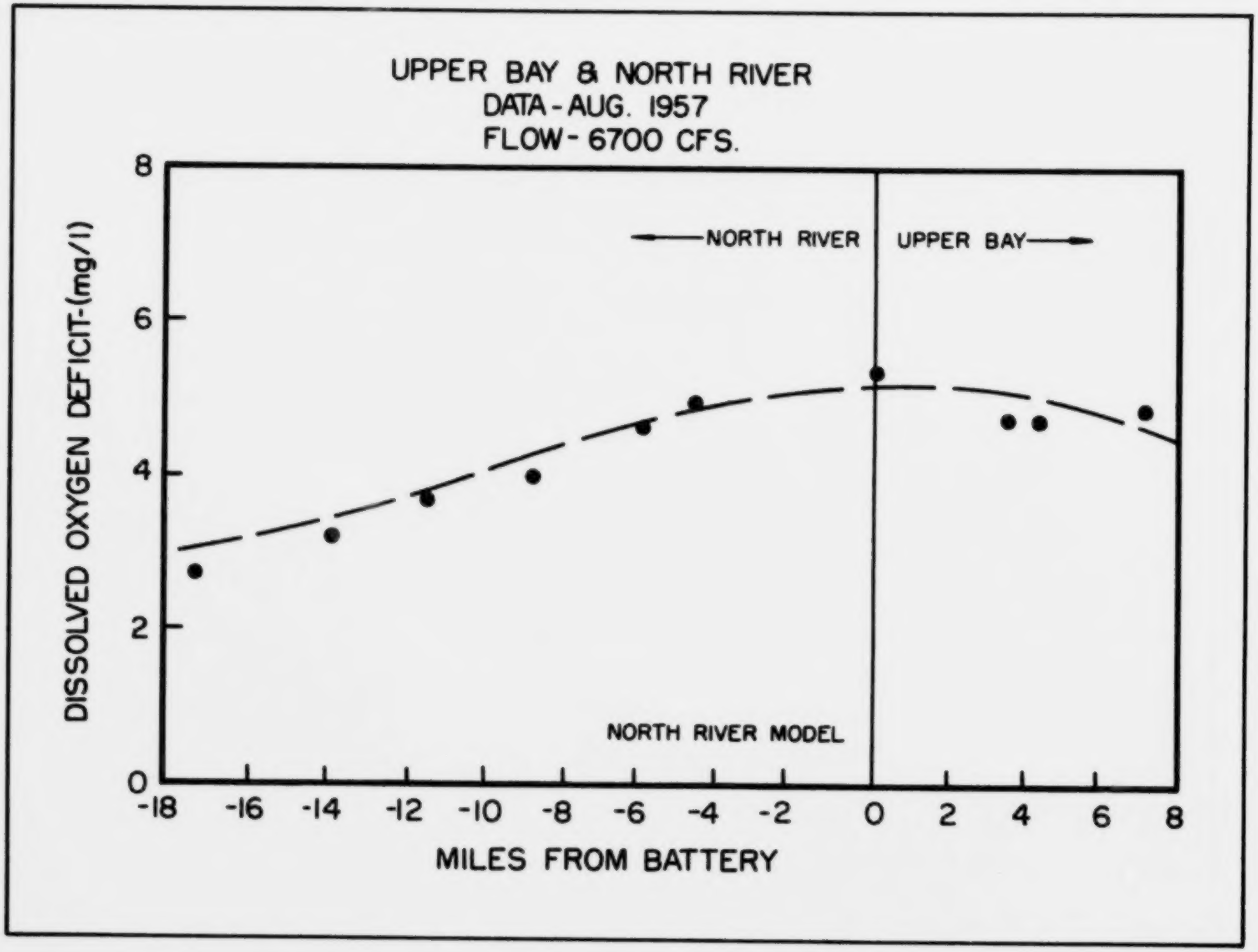

UPPER BAY & NORTH RIVER
DATA - AUG. 1957
FLOW - 6700 CFS.
DISSOLVED OXYGEN DEFICIT-(mg/l)
8
6
4
2
0
←NORTH RIVER
UPPER BAY→
NORTH RIVER MODEL
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
MILES FROM BATTERY

FIGURE 37

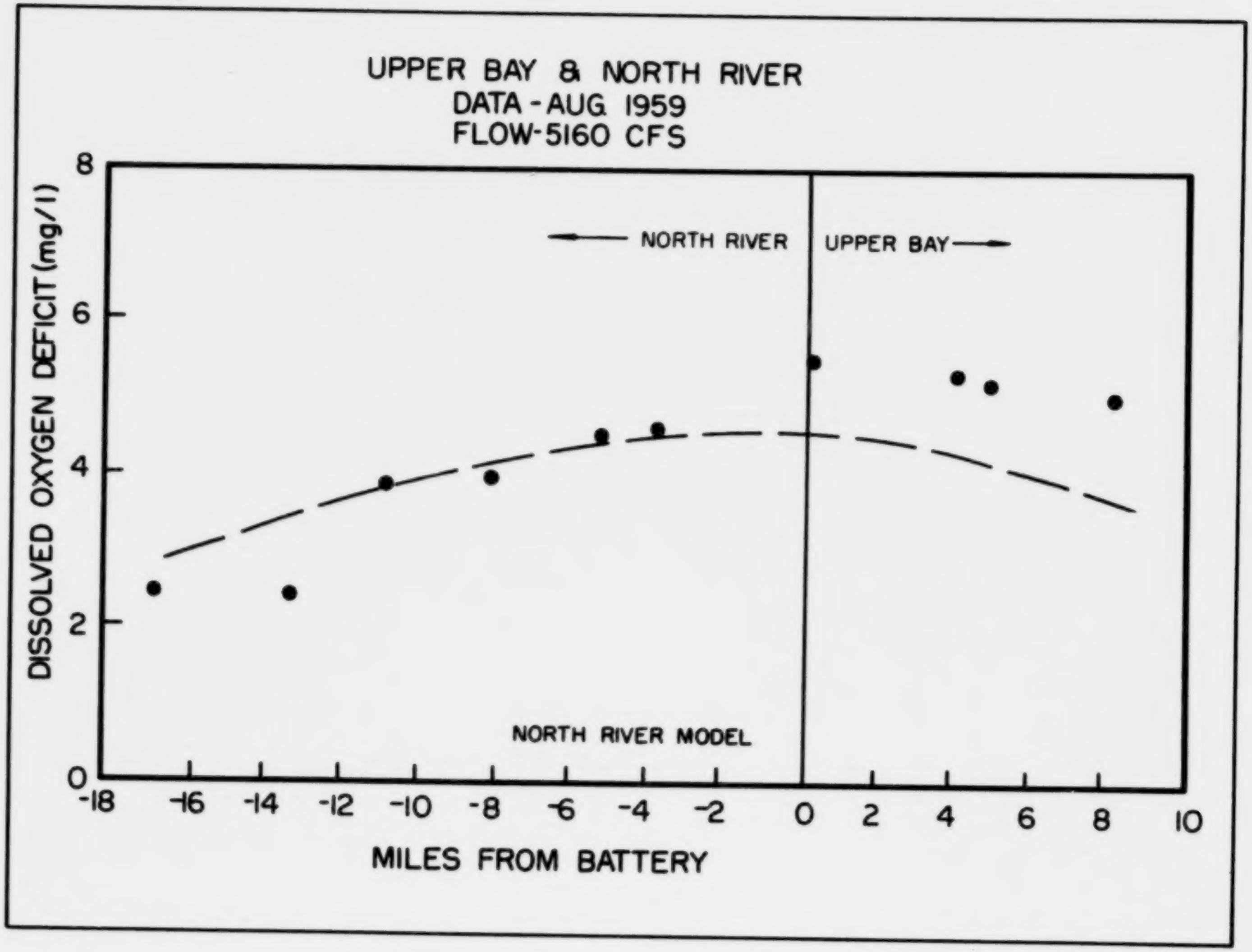

UPPER BAY & NORTH RIVER
DATA - AUG 1959
FLOW-5160 CFS
DISSOLVED OXYGEN DEFICIT (mg/l)
0
2
4
6
8
NORTH RIVER
UPPER BAY
NORTH RIVER MODEL
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
MILES FROM BATTERY

FIGURE 38

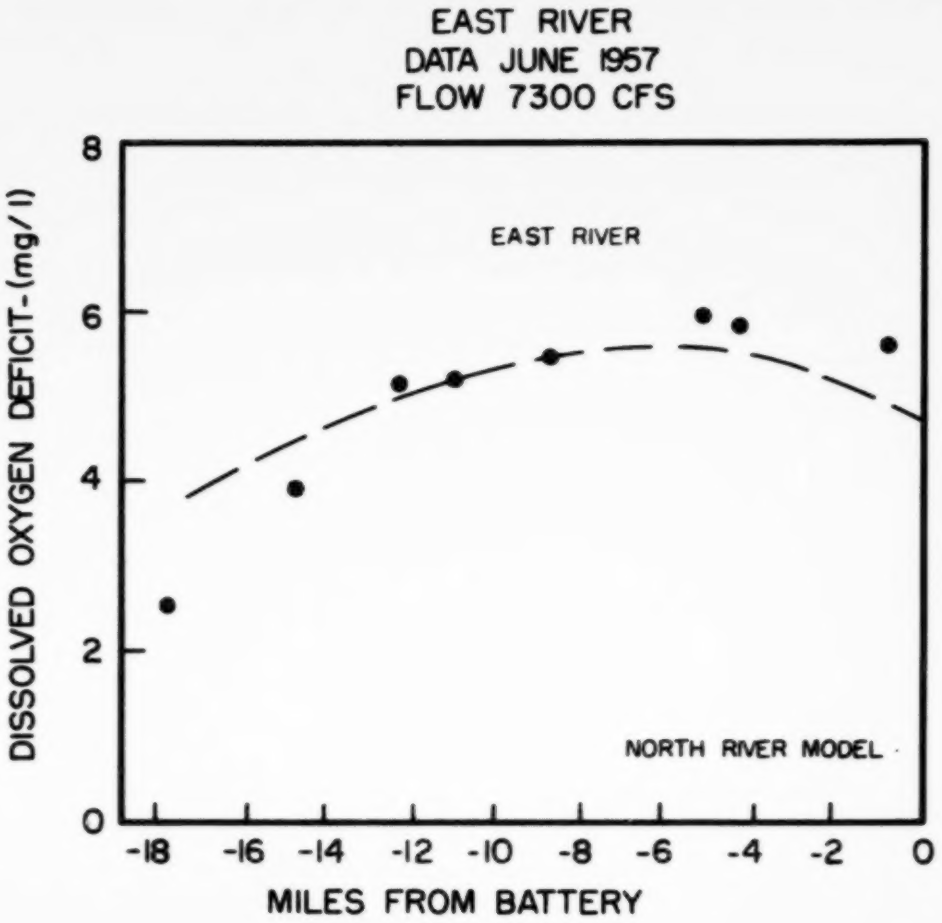

EAST RIVER
DATA JUNE 1957
FLOW 7300 CFS
EAST RIVER
NORTH RIVER MODEL
DISSOLVED OXYGEN DEFICIT-(mg/l)
8
6
4
2
0
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
MILES FROM BATTERY

FIGURE 39

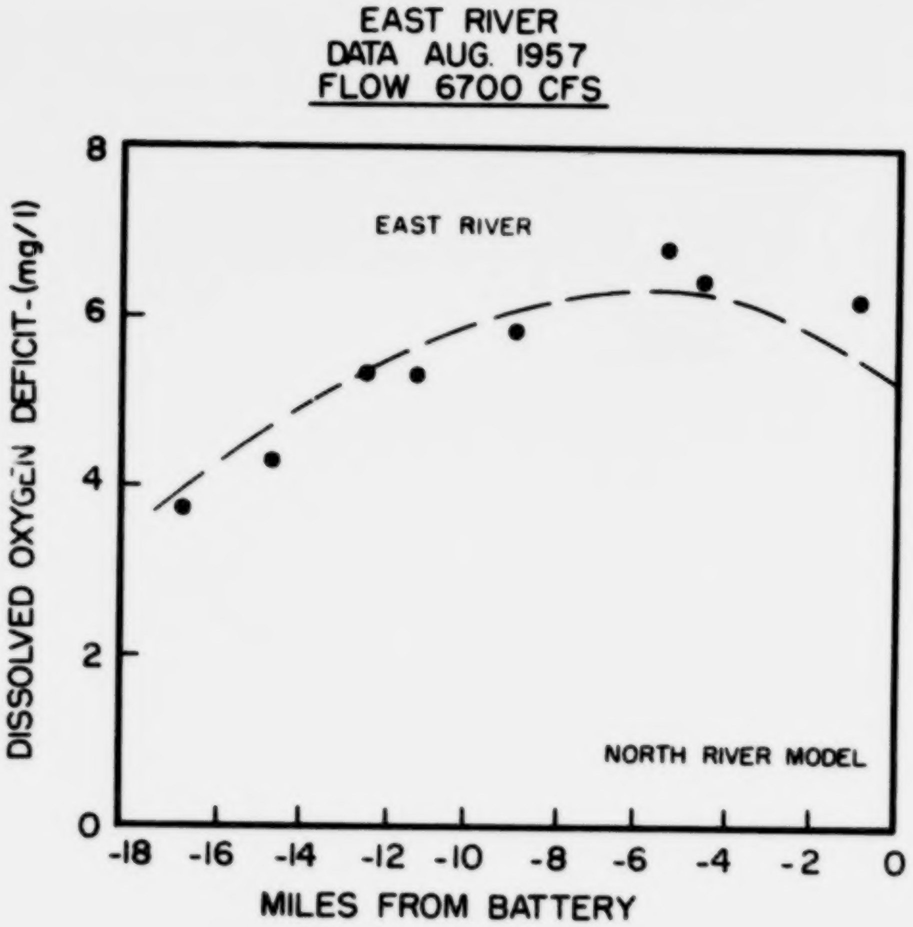

EAST RIVER
DATA AUG. 1957
FLOW 6700 CFS
EAST RIVER
NORTH RIVER MODEL
DISSOLVED OXYGEN DEFICIT-(mg/l)
8
6
4
2
0
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
MILES FROM BATTERY

FIGURE 40

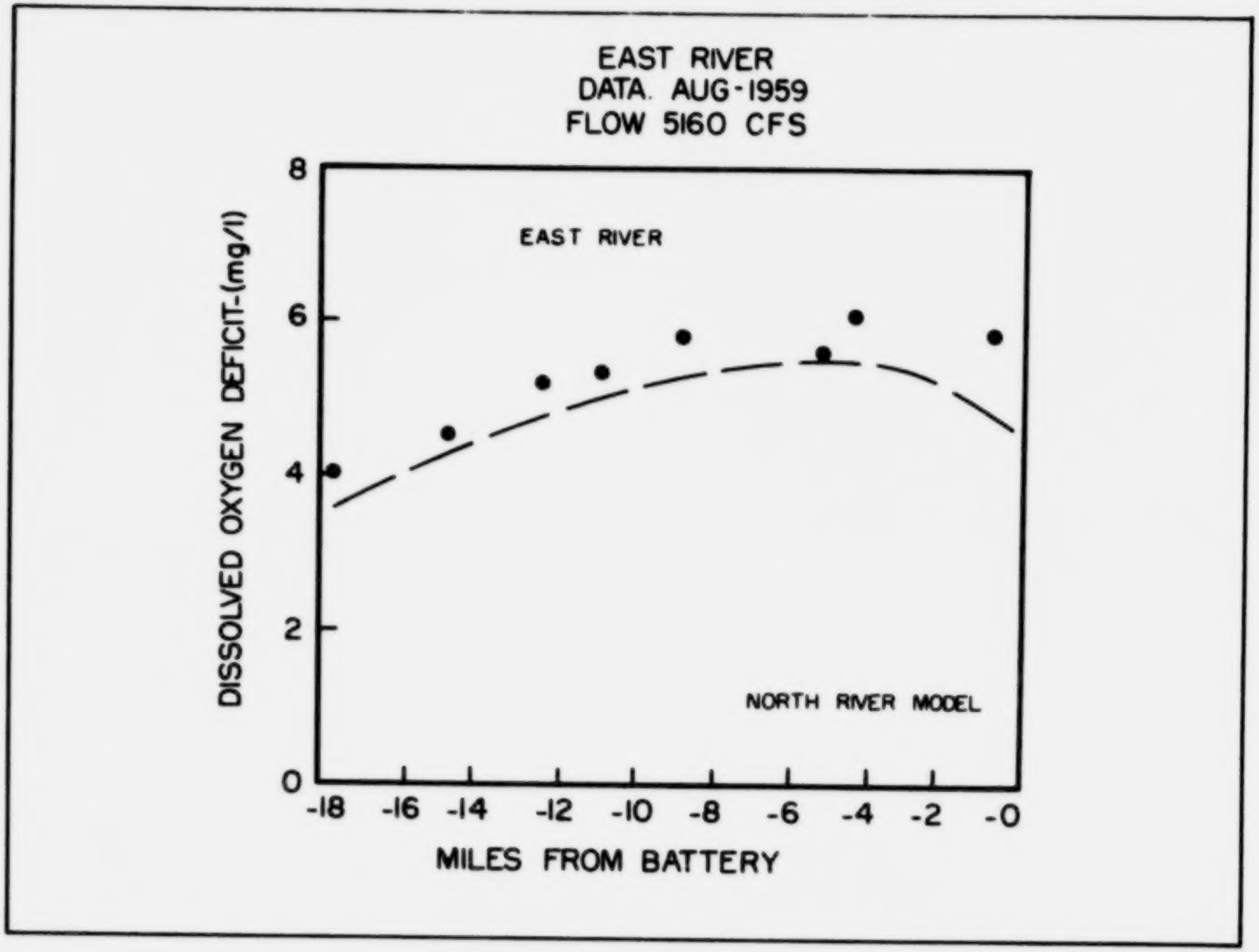

EAST RIVER
DATA. AUG-1959
FLOW 5160 CFS
EAST RIVER
NORTH RIVER MODEL
DISSOLVED OXYGEN DEFICIT-(mg/l)
8
6
4
2
0
-18
-16
-14
-12
-10
-8
-6
-4
-2
-0
MILES FROM BATTERY

FIGURE 41

included in the North River water quality model. The verification of the model employed to obtain the calculated profiles in the East River portion of the North River model is therefore questionable. Use of the analysis technique for complex estuaries would strengthen the analysis.

This report presents estimates of waste loadings and parameters which can be employed to obtain a first-cut approximation of the water quality within the system. There are several specific steps which can be employed to advance the analysis and strengthen the available understanding of the phenomena influencing water quality. These procedures are:

1. Observed water quality data available on the New York Harbor Complex has been, for the most part, collected without consideration of the tidal influence. The initial suggested step is to reduce this background of observed water quality data to locate all data in terms of a common point in the tidal cycle. This procedure will increase the usefulness of these data in two respects. In the first instance data which is located with respect to a common point in the tidal cycle will provide much more reliable water quality profiles to be employed in verification of the mathematical models. A second

benefit occurring from having data located with respect to a common position in the tidal cycle is obtained from an analysis of these data regarding the anticipated variation of water quality at each station. That is, data could be subjected to a regression type analysis which would result in indications of water quality trends as related to time and an indication of the random variation of observed water quality. This analysis would provide an indication of the relative effectiveness of the treatment facilities which have been installed. Further, the random variations would quantitize the water quality levels which are required to insure meeting of water quality objectives on a statistical basis.

2. There is a significant lack of information on the nitrogenous material in the receiving bodies throughout the entire study area. It is suggested that data be collected on nitrogenous matter and on oxidation of nitrogenous material. With the removal of BOD by conventional treatment plant designs, the relative oxygen demand associated with nitrogenous matter can become the phenomenon which limits the ability to achieve water quality goals. An illustration of the potential significance of nitrogenous oxidation on dissolved oxygen profiles is

obtained by a comparison of the ultimate oxygen demand of a secondary effluent. Assuming an effluent BOD of 20 mg/l for carbonaceous material and an NH_3 concentration of 20 mg/l, the approximate ultimate oxygen demands are 30 mg/l and 90 mg/l for carbonaceous and nitrogenous oxidation respectively.

Information on the nitrogenous content of waste inputs and on the oxidation of nitrogenous material in the receiving waters will provide a basis on which predictions of water quality after treatment can be developed. An additional phenomenon which has a significant impact on predicted water quality after installation of treatment facilities is the sensitivity of nitrogenous oxidation rates to dissolved oxygen level. Dissolved oxygen concentrations below 2 to 3 mg/l appear to inhibit the rate of nitrogenous oxidation.[1] Thus, when carbonaceous BOD is removed by treatment, and water quality improves, the nitrogenous oxidation is accelerated, tending to return water quality to the level before treatment. An added complication, which can be significant, is found in consideration of estuary geometry. In estuaries which have rapidly changing cross-sectional areas, the larger area portions of the system can have water quality profiles which are insensitive to treatment when associated with acceleration of nitrogenous oxidation. By way of illustration, consider the removal of a quantity of BOD from an estuary section having a cross-sectional area of 4500 square feet, and the discharge of this BOD in an estuary section having a cross-sectional area of 1500 square feet (this is in effect what can result when nitrogenous oxidation is accelerated). If the improvement in water quality in the larger estuary section is 0.2 mg/l, the resultant decrease in water quality in the smaller estuary section will be 0.6 mg/l. This is precisely the type of phenomenon which may occur in large estuarine complexes like New York Harbor. Treatment allows the nitrogen oxygen demand to be exerted in the smaller cross-sectional area portions of the estuary, which in effect reduces the quantity of oxygen demand being exerted in the larger cross sectional area portion of the estuary. The net result is a small improvement in the water quality of the large cross-sectional areas of the estuary, and minimal improvement near the discharge location.

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[1] "Effects of Polluting Discharge on the Thames Estuary," Water Pollution Research Laboratory, Technical Report No. 11, HMSO, 1964.

3. A third area of investigation which would strengthen the verification procedure for water quality models is in the assessment of waste input loads and better evaluation of specific sources and sinks of polluting substances and oxygen deficit as follows:

a. Raw Discharges of both treated and untreated waste waters.

b. Storm overflow from combined and separate sewer systems (urban runoff).

c. Bottom deposits as sinks of dissolved oxygen and as sources of BOD and nitrogenous matter.

d. Non-urban runoff contribution of pollutional substances and nutrients.

e. Long term oxygen utilization of samples of the various waste waters and estuarine waters.

The significance of reliable and complete identification of sources and sinks of pollution can be illustrated by crudely considering that predictions of future water quality are made in the following manner:

Consider a situation in which two 100 pound sources of continuous waste discharge provide a deficit of 8 mg/l and are the only pollution thought to be entering the body of water. Let us consider further that in reality each source is only 90 pounds and 20 pounds is from a third source which is unknown. In developing predictions let us assign a 90 percent removal to our two known sources. A dissolved oxygen deficit of 0.8 mg/l would be predicted while, in reality, 90 percent treatment of the two known sources would result in a deficit of 1.12 mg/l. This is an error in prediction of some 40 percent (.32/ .8) from a 10 percent error in load assignment. It is possible to consider that the third source was actually non-urban runoff, bottom deposits, nitrogen oxidation or other sources.

The magnification of errors in assignment of system inputs, when prediction is considered, strongly recommends the expenditure of funds to define present and future sources.

The example describing the magnification of error has equal bearing on the general ability to achieve water quality objectives regardless of whether modeling of water quality is employed. Incomplete assessment of present loading and the phenomenon controlling existing water quality can, because of magnification effects and the nitrogen phenomenon, result in minimal improvement in quality actually resulting after large expenditure for control facilities.

LAKES :

Water quality in lakes can be viewed in three distinct perspectives. In the first instance, one can consider a lake in the sense of geological time. A mass balance around the lake considering a specific substance which can influence water quality is developed. The rate of accumulation of these substances can be evaluated to assess long-range trends in water quality. The second perspective for water quality considers local pollution in the vicinity of streams or outfalls entering a lake. This analysis is similar in concept to those presented for streams and estuaries in that proper evaluation of the phenomena of advection, decay and dispersion results in equations which can be employed to define concentration profiles of substances influencing water quality or usage. The third perspective of water quality in lakes considers the body of water as a vertically stratified system. In this latter case, the vertical profiles of water temperature and pollutional substances are defined thus providing an initial step in evaluating water quality.

Long Term Water Quality in Lakes

A lake may be considered in the sense of a body of water whose water quality alters in a geological time scale of years, decades or centuries. Consider the body as completely mixed with the periods of analysis extending from autumn or spring turnovers.

A mass balance around a lake can be developed considering that at time " t " the concentration is " C " and at a finite time interval, Δt, the concentration changed to " $C + \Delta C$ ". The mean concentration can be assigned as " $\overline{C}$ " for the finite time interval. The change in mass over the time interval equals the amount entering minus that leaving, plus sources minus sinks.

$$\Delta C_L \cdot V_L = W_L \cdot \Delta t - \overline{C}_L \cdot V_L \cdot K_L \cdot \Delta t - Q \cdot \overline{C}_L \cdot \Delta t \qquad (\ 55\ )$$

As $\Delta t \longrightarrow$ approaches zero, $\overline{C} \longrightarrow C$, and ΔC approaches dC, equation (55) becomes :

$$V_L \cdot dC_L = W_L\, dt - C_L \cdot V_L \cdot K_L \cdot dt - C_L \cdot Q \cdot dt \qquad (\ 56\ )$$

All symbols used in this section of the report are defined in the lake nomenclature.

Grouping Terms:

$$\frac{dC_L}{dt} = \frac{W_L}{V_L} - C_L \cdot \left(\frac{Q}{V_L} + K_L \right) \qquad (\ 57\ )$$

Integration with $C_L = C_o$ @ $t = 0$ yields:

$$C_L = C_o e^{-t \cdot \left[\frac{Q}{V_L} + K_L \right]} + \frac{W}{Q + V_L K_L} \left[1 - e^{-t \cdot \left[\frac{Q}{V_L} + K_L \right]} \right] \qquad (\ 58\ )$$

Equation (58) is for a non-conservative substance. Employing the same reasoning and mathematical techniques, and considering a non-conservative substance with an additional sink, for example, settling of material, yields equation (59) .

$$C_L = C_o e^{-t}\left[\frac{Q}{V_L} + R_L + K_L\right] + \frac{W_L}{Q+V_L K_L + R_L K_L}\left[1-e^{-t}\left[\frac{Q}{V_L} + K_L R_L\right]\right] \qquad (59)$$

in which R_L is the exchange rate listed in the lake nomenclature.

If in addition the bottom also is considered as a source of material, then equation (   ) is obtained:

$$C_L = C_o e^{-t}\left[Q/V_L + K_L + R_L\right] + \frac{W_L + C_B R_B V_B}{Q+V_L K_L + R_L V_L}\left[1-e^{-t}\left[\frac{Q}{V_L} + K_L + R_L\right]\right] \qquad (60)$$

Equations (58) to (60) can be employed to predict the concentration of a substance as a function of time when $C_L = C_o$ at $t = 0$. If the substance is non-reactive or conservative, then K_L equals zero. If the bottom does not act as a source or sink, then R_L and R_B are equal to zero. Note that C_B is assumed to be time-invariant.

In all of the cases indicated above, it is evident that the equilibrium concentration is defined by :

$$\frac{dC_L}{dt} = 0 \qquad (61)$$

therefore, equation (60) becomes :

$$C_B \cdot R_B \cdot V_B + W_L = QC_e + K_L \cdot V_L \cdot C_e + R_L \cdot V_L \cdot C_e \qquad (62)$$

and

$$C_e = \frac{W_L + C_B \cdot R_B \cdot V_B}{Q + K_L \cdot V_L + R_L \cdot V_L} \qquad (63)$$

The concentration tends to increase for an infinite time, thus it is theoretically impossible employing equations (58) to (60) to reach the equilibrium concentration. In practice, one can select any practical percentage of the equilibrium concentration for computational purposes.

In applying equations (58) to (60) to predict water quality, it must be emphasized that the waste input " W_L " and the parameters defining the phenomena occurring in the lake are all considered with time invariant. Simple time variable functions may be included in the basic equation and integrated directly. For highly variable and erratic changes in time, it is possible to segment the time dimension in a manner comparable to segmentation of the length dimension " X " in stream and estuary problems.

Of particular significance from a time varying point of view is the input "W_L" which would tend to increase as a function of time as a result of population increases and industrial expansion.

It is possible to consider a lake as a two-layered body in the geological scale of years, decades and centuries. In this instance, a lake is composed of an upper layer and a bottom layer which can act as a sink and/or source of material.

Allowing the concentration of material to change as a function of time in both layers results in the two differential equations :

Top Layer

$$\frac{dC_L}{dt} = \frac{C_L R_L V_L}{V_B} - C_B \left(R_B V_B + K_B V_B \right) \qquad (64)$$

Bottom Layer

$$\frac{dC_B}{dt} = \frac{C_L R_L V_L}{V_B} - C_B \left(R_B V_B + K_B V_B \right) \qquad (65)$$

Separation of variables and integration results in :

Top Lake

$$C_L = ML_e^{M(t)} + NL_e^{N(t)} + YPL \qquad (66)$$

where:

ML and NL are constant to be determined by the boundary conditions.

$$YPL = \frac{W_L \left[R_B + K_B\right]}{V_L} \left[\frac{1}{Q/V_L + R_L + K_L + R_B + K_L - R_L R_B}\right] \qquad (67)$$

Roots " M " and " N " equal :

$$- \left[\frac{Q/V_L + R_L + K_L + R_B + K_B}{2}\right]$$

$$\pm \left[\left[\frac{Q/V_L + R_L + K_L + R_B + K_B}{2}\right] - \left[\left[Q/V_L + R_L + K_L\right]\left[K_B + R_B\right]\left[-R_L R_B\right]\right]\right]^{1/2}$$

Bottom

$$C_B = MB_e^{M(t)} + NB_e^{N(t)} + YPB \qquad (68)$$

where:

MB and NB are constants to be determined by the boundary conditions.

$$YPB = \frac{W_L \cdot R_L}{V_L} \left[\frac{1}{Q/V_L + R_L + K_L + R_B + K_L - R_L R_B} \right] \qquad (69)$$

Roots " M " and " N " are the same as for the top lake solution.

Equations (66) and (68) can be applied to evaluate the concentration of a reactive substance in the liquid portion of the lake and in the bottom sediments respectively. The bottom sediment must be defined as that portion of the lake bottom which has an influence on water quality. " W_L " has been assumed constant with respect to time. It is again possible to evaluate changes in " W_L " and the other parameters by segmenting the system in the time dimension. Equations (66) and (68) contain two unknown coefficients each. The specific boundary conditions for evaluating these unknowns are:

$$@\ t = t_1 \quad C_L = C_{Lo} \text{ and } C_B = C_{Bo}$$

$$@\ t = t_1 \quad \frac{W_L}{V_L} + \frac{V_B R_B}{V_L} \cdot C_B - C_L\ Q/V_L + R_L + K_L = \frac{dC_L}{dt}$$

and:

$$\frac{V_L R_L C_L}{V_B} - C_B\ R_B + K_B = \frac{dC_B}{dt}$$

Lakes As Stratified Bodies

Temperature Gradients (Continuous Functions)

The vertical distribution of temperature in lakes and oceans can be represented by a form of Equation (70). The assumption is usually made that the advection and source terms are negligible. The temperature is not strictly a concentration, but since it is proportional to the heat content of a unit volume, the symbol "T" may represent the temperature. This equation was developed by considering the amount of heat per unit time which passes through a unit area. In this form, the equation for heat transfer may be written:

$$\frac{\partial \theta}{\partial t} - E \frac{\partial T}{\partial y} \qquad (70)$$

The term, "θ" is the total heat which passes through a unit area at depth, "y". Equation (70) has been applied directly to data on temperature, particularly in the field of limnology (Hutchinson, Treatise on Limnology, Volume I). The procedure consists in computing the rate of increase in the heat content of a column between two depths over an interval of time. This value is then divided by the mean thermal gradient to obtain the eddy conductivity. The values thus obtained for the hypoliminon ranged from one to 200 or 300 sq. cm. per second, and are evidently correlated to the depths and surface areas of the lakes considered.

Although there are a number of assumptions involved in the computation, it does indicate a realistic order of magnitude with the majority of the values in range of 10.

If a balance about a differential element is performed, it has been shown that Equation (70) is modified to :

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial y} \left(E \frac{\partial T}{\partial y} \right) \qquad (71)$$

Equation (71) is the simplified form of Equation (70), in which the advection and source terms are considered negligible. As a boundary condition, assume the temperature in the surface layer varies in a periodic fashion, and as an initial condition that the temperature is zero.

$$T = 0 \quad t = 0 \quad X > 0$$

$$T = To + Tm \cos at \quad X = 0 \quad t > 0$$

Where " a " is the frequency $= \frac{2\pi}{p}$ for a period, " p " .

The solution of Equation (71) for these conditions consists of two parts; one, a transient caused by initiation of the period temperature at the surface, which decays as time increases, leaving the second part, which is the periodic steady state. The latter part of the solution, which is of practical significance, is :

$$T = T_o + T_m e - \left(\frac{ay^2}{2E} \right) \quad \cos \left\{ at - \left(\frac{ay^2}{2E} \right) \right\}^{2} \qquad (72)$$

In some cases, it is more appropriate to represent the temperature as a Fourier series. Analysis of the diurnal change in temperature in the ocean indicates a constant eddy conductivity in the upper homogenous layer of the ocean. The annual or seasonal change usually requires a variable coefficient both in depth and time. Its value is maximum at the surface and during the spring. It is probable that comparable conditions occur in lakes.

The range is of the same magnitude as that reported for lakes, 1 - 300 sq.cm. per second, but the majority of the data are in the order of 50 for the oceans, as compared to 10 for the lakes.

Further application of Equation (72) has been made on temperature data in lakes. It is observed that in the thermocline and the upper part of the hypoliminar, the temperature decreases exponentially with depth. The temperature in this case is that after the minimum isothermal temperature has been subtracted, " T_o " . From this, it may be shown that the time variation also decreases exponentially with depth.

$$(T - T_o) = C_e^{-ay} \tag{73}$$

C is either the surface temperature which would be observed if the temperature curve were extrapolated to the surface or that temperature at the bottom of the epiliminon. The axis, ($y = o$) is established at whichever datum is selected. If this expression is differentiated twice with respect to depth and substituted into Equation (73), the result is as follows :

$$\frac{(T - T_o)}{t} E_a{}^2 C_e{}^{-ay} = E_a{}^2 (T - T_o) \qquad (74)$$

If these relationships are valid, then a linear relationship exists between the depth and the logarithims of T and $\frac{T}{t}$. A plot of such data would yield the value of conductivity as determined from the slopes of the lines. Alternately, Equation (74) also indicates that the temperature increases exponentially with time. Therefore, a plot of the logarithim of temperature versus time should yield a linear relation, whose slope is $E_a{}^2 C$. The exponent, " a " is determined from depth, temperature, and the value, " C ", from the data. Values computed by this method are lower than those computed by Equation (72). The range for a number of lakes and ponds of relatively shallow depth is from 0.001 to 0.05 sq. cm. per second.

Two-Layered System

An interim approach to the problem of vertical stratification in lakes considers a lake as a two-layered system with exchange and reaction between a top and bottom layer. The time scale under consideration in this particular situation is in the order of days, weeks or months. It is possible to segment the stratification pattern of lakes in the time dimension and apply the two-layered solutions to each time period. The specific equations which are applicable to this situation are as follows:

Top Layer

$$C_t = B_t e^{ST(t)} + A_t e^{VT(t)} + YPT \tag{75}$$

B_t and A_t equal constants defined by boundary conditions.

$$ST = -\left[\frac{b + KB + RB}{2}\right] + M$$

$$VT = -\left[\frac{b + KB + RB}{2}\right] - M$$

$$b = Q/V_T + RT + KT$$

$$M = \frac{b + [KB + RB]^2}{4} - \left[b\,[KB + RB] - RTRL] \right]^{1/2}$$

$$YPT = \frac{WF\,[RB + KB]}{VT\left[b + [RB + KB] \quad - R_t RB\right]}$$

Bottom Layer

$$C_B = B_B e^{SB(t)} + A_B e^{VB(t)} + YPB \tag{76}$$

B_B and A_B equal constants defined by boundary conditions.

$$SB = ST$$

$$VB = VT$$

$$YPB = \frac{W_T \cdot R_T}{V_T \left[b + \left[RB + KB \right] - R_T RB \right]}$$

Note that Equations (75) and (76) are identical in form to Equations (66) and (68). The basic assumptions upon which Equations (75) and (76) are developed are that the volumes of the top and bottom layers are constant with respect to time. Segmentation in the time dimension would result primarily from changes in the volume of top and bottom layers and from variations in the reaction rates resulting from seasonal temperature changes.

Local Pollution :

A significant characteristic of water quality in lakes and similar bodies of waters is the distribution of any contaminant in the vicinity of a river discharge or a sewer outfall. The river water, with its pollutional material load, is initially diluted by the turbulence of the discharging stream into the surrounding water. After the initial jet mixing, further dilution occurs due to the natural turbulence in the lake. The concentration of bacteria at any point in the lake beyond the zone of initial mixing is a function of turbulent diffusion and also of the natural die-away. Considering the surface plane or zone, the steady-state distribution of the bacterial concentration may be described by the following equation:

$$O = E_x \frac{\partial^2 c}{\partial x^2} + E_y \frac{\partial^2 c}{\partial y^2} - Kc \qquad (77)$$

The x and y axes are defined as shown in Figure 42. In Equation (77) constant coefficients in both the longitudinal and lateral directions are assumed and the die-away rate of the bacteria is taken as a first-order reaction. Operation of the axis is shown in Figure 42 . If it is further assumed that the diffusion coefficients are equal in each direction, then Equation (77) becomes :

$$O = E \left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} \right) - Kc \qquad (78)$$

When there is a significant wind velocity and the associated water current, an advective term resulting from this effect must be included in Equations (77) or (78) .

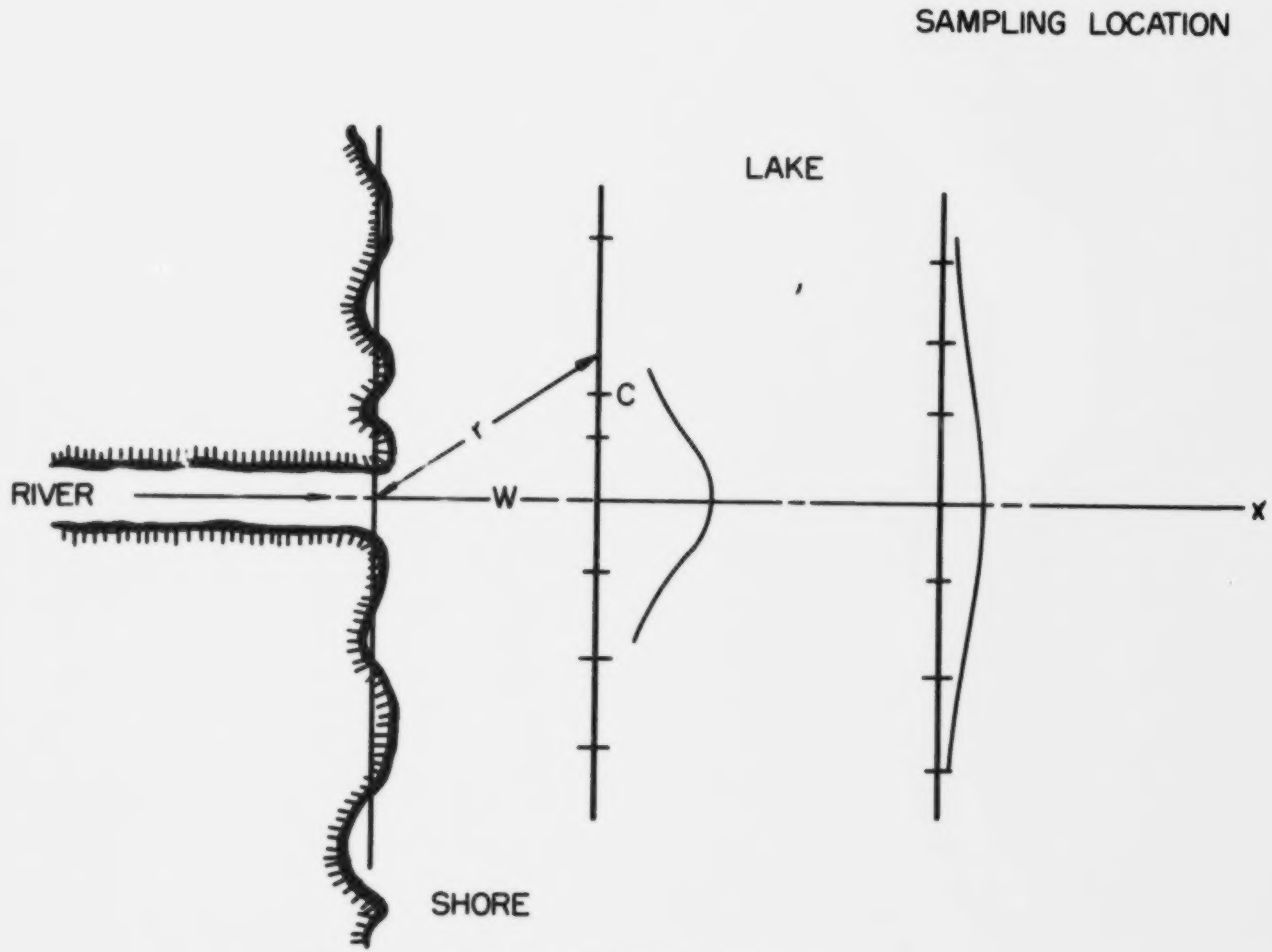
For convenience, the Equation (78) is transformed to polar coordinates and yields:

$$\frac{\partial^2 c}{\partial_r^2} + \frac{1}{r} \frac{\partial c}{\partial r} + \frac{1}{r^2} \frac{\partial^2 c}{\partial \theta^2} - \frac{Kc}{e} = 0 \qquad (79)$$

Under the assumption that " c " is constant for a given " r " .

$$\frac{\partial c}{\partial \theta} \quad \text{and} \quad \frac{\partial^2 c}{\partial \theta^2} = 0$$

This assumption does not strictly apply to the vicinity of the shore, where


SAMPLING LOCATION
LAKE
C
r
RIVER
W
x
SHORE

TYPICAL CONCENTRATION PATTERNS

FIGURE 42

the concentration patterns are overlapped by reflection and other sources of pollution, but may apply to a zone radiating from the point of the river outlet and defined by radii 45° on either side of the X-axis. For this zone, the partial differential Equation (79) reduces to the following ordinary differential equation :

$$\frac{d^2c}{dr^2} + \frac{1}{r}\frac{dc}{dr} - \frac{K}{E}c = 0 \qquad (80)$$

which is a Bessel equation of order zero. The solution of Equation (80) is:

$$C = AI_o\left[\sqrt{\frac{Kr^2}{E}}\right] + BK_o\left[\sqrt{\frac{Kr^2}{E}}\right] \qquad (81)$$

in which I_o and K_o are modified Bessel functions of the first and second kinds and A and B are constants. Subject to the boundary conditions that

$$c = 0 \qquad r = \infty$$

$$c = c_o \qquad r = r_o$$

the final equation is:

$$C = \frac{C_o}{M} K_o \left[\sqrt{\frac{Kr^2}{E}}\right] \qquad (82)$$

in which

$$M = K_o\left[\sqrt{\frac{Kr_o^2}{E}}\right]$$

When the wind velocity is significant, an advective term must be included in Equation (79) . In this case, the concentration pattern, as developed above, is distorted by a projection along the axis of the wind velocity. Thus elements of fluid containing higher concentration of bacteria are translated to larger distances from the shore. In order to simplify the basic differential equation, the assumption is sometimes made that diffusion is negligible along the X-axis because of the convection in this direction. Furthermore, it has been observed that the coefficient of lateral diffusion does not remain constant with distance, but varies as the scale of the diffusion phenomenon. This effect was first reported by Richardson, who empirically observed that the coefficient varied as the 4/3 power of the scale. A theoretical basis for this relationship has been presented in similarity hypothesis of Kolmogoroff. Under these conditions, Equation (79) for the steady-state becomes :

$$O = \frac{\partial}{\partial y} \left(E_y \frac{\partial c}{\partial y} \right) - U \frac{\partial c}{\partial x} - Kc \qquad (83)$$

By relating the variation of the lateral diffusion coefficient to the longitudinal dimension in accordance with the 4/3 power relationship, Brooks integrated Equation (83) for the $y = O$ axis.

$$C = C_o e^{-\frac{Kx}{U}} \operatorname{erf} \left[\sqrt{\frac{3/2}{\left(1 + \frac{8E_o x}{Uw^2} \right)^3 - 1}} \right] \qquad (84)$$

If the diffusion coefficient is assumed as a constant, then Equation (83) integrates as follows:

$$C = C_o e^{-\frac{Kx}{U}} \operatorname{erf} \sqrt{\frac{Uw^2}{16\,Ex}} \qquad (85)$$

DISCUSSION - LAKES :

The equations presented in this report on the distribution of substances in lakes are neither necessarily definitive nor final descriptions of the various phenomena, but are possible mathematical models which may at least be employed to correlate laboratory and field data. The formulations presented do indicate the significance and relative impact of the various phenomena of dispersion, reaction, convection, exchange and advection on water quality in lakes.

Various parameters, geometrical and water quality measurements are required before the equations presented in this section of the report can be used. Each of the three perspectives for lake water quality require different field programs. The measurement programs are related to the basic assumptions, definition of terms and parameters employed in the developments of the several equations. The water quality data on Lake Champlain could not be employed to meaningfully validate the models presented.

The following discussion will indicate the basic assumptions employed in the developments and suggest in qualitative terms the field measurement required to verify the mathematical models and evaluate a consistent set of system parameters.

1. Long term water quality models are presented in Equations (58) to (60). It will be noted that Equation (60) contains all of the terms in Equations (58) and (59), and in addition, the lake bottom is considered a source term.

   The concentrate C_L within the lake is defined as the average concentration. There are several possible patterns of field measurements which can be employed to define this concentration. The simpliest method is to relate field measurements for specific points in the annual cycle of the lake. In particular, the autumn turnover might be appropriate. Inherent in this approach is the inaccuracy resulting from the assumption that the specific concentration used as the basis of comparison is the average concentration present in the lake.

In particular, the basic differential equation employs the reaction term, $C_L \cdot V_L \cdot K_L \cdot dt$, and the advective term $C_L \cdot Q \cdot dt$. In both terms the value of C_L should be an average concentration value in space and time. The concentration at a specific point in time need not be the average concentration over the year. It is possible, however, to compensate for the use of a single concentration (such as that associated with the autumn turnover,) by considering KL the apparent reaction rate. Mention has been made in this discussion of average concentrations in time and space and the apparent discharge rate. The term as employed has the following interpretation :

1. The average concentration in space and time within the lake is determined from continuous or periodic measurements throughout the lake which provide an accurate measure of concentration for a known portion of the lake volume over a known period of time. The specific concentrations can then be numerically integrated by summing the produce of the concentration, the associated volume and time period. The resultant quantity is divided by the summation of the product of the volume and time interval.

$$\bar{C}_L = \frac{\sum C_L \cdot V \cdot \Delta t}{\sum V \cdot \Delta t}$$

2. An equivalent procedure is applicable to establishing the average discharge from the lake. In this instance, continuous or periodic measurement of the concentration leaving the lake is

determined for a known rate of flow and a known period of time over which this flow rate persists. The equivalent numerical integration technique is defined by :

$$\bar{\bar{C}}_L = \frac{\sum C_L \cdot Q \cdot \Delta t}{\sum Q \cdot \Delta t}$$

The apparent average discharge from the lake is then calculated by :

$$Q = \frac{\sum Q \cdot \Delta t}{\sum \Delta t} \quad \frac{\bar{C}_L}{\bar{\bar{C}}_L}$$

From a practical standpoint, it is doubtful that the expense involved in collecting the data required for calculating average concentrations in space and time can be justified solely for use in the models to evaluate long-term water quality trends. However, comparable data could be employed in the other mathematical models. It must be emphasized that this represents a significant sophistication and greater experience and understanding of the behavior of lakes would appear to be indicated before attempting to collect this type of data on a large scale.

In Equations (66) and (68) exchange terms " R_L " and " R_B " are employed. These factors can describe the phenomena of accumulation of material on the bottom of a lake and the potential reintroduction of this material, perhaps in altered form, into the liquid portion of the lake. An oversimplified example of the use of this concept may be presented using phosphate as an illustration. Phosphate may enter the lake system in sewage, industrial waste discharge, and inorganic matter carried in by surface and ground waters. A major portion of the phosphate entering the lake may initially be complexed and settle to the bottom. This removal phenomenon would be described by the "R_L" parameter. Subsequent decomposition of the complexes originally formed may enable the phosphate to re-enter the system in an available form for use by algae. The re-entry of phosphate into the lake environment may be enhanced by circulation currents in the spring and fall of the year. The phenomenon of re-entry may be defined by the parameter "R_B".

Development of measures of these exchange phenomena present extremely complex measurement problems. It is, however, doubtful if a true evaluation of lake behavior and water quality can be obtained without consideration of the lake bottom as both a potential source and sink of material.

The quantity "C_B" in Equation (65) is subject to the same considerations as the quantity "C_L" Some typical annual value should be adequate in initial computations. A time and space average value may prove desirable at some future time.

Volume terms "VL" and "VB" are employed in Equations (75) to (76). These volumes are defined as active volumes which are involved in the changes of lake water quality. In general, "VL" would include all major liquid portions of the lake. "VB" is assigned as the active volume of bottom sediment. Errors in measuring or assigning "VB" will alter the values of " RB " and " KB ".

The final parameter of concern in the subject equations is the input term, " WL ", which represents the mass of material introduced into the lake per unit time. In actuality, this term should contain estimates for all sources of the constituent understudy. That is, material carried into the lake by surface water, direct discharges, ground water and airborne, (leaves, etal.,) should be evaluated. In like manner airborne material carried out of the lake should be subtracted from " WL ".

The comments offered with regard to the several parameters in Equation (64) to (69) are directly applicable to the comparable parameters in Equations (75) and (76). In addition, one may consider the reaction term " KB " for substances which are not truly reactive in a chemical or biological sense as a measure of material which enters the inactive portion of the lake bottom.

The equations which describe temperature gradients in a lake require field programs for evaluation of the vertical temperature gradients as a function of time. It is desirable initially to evaluate the temperature gradients as a function of time in several representative lake locations. This will provide the basic information required to integrate the several equations.

The degree of additional temperature information required will only be defined after preliminary application of the temperature equations.

The comments made with respect to average concentration values in time and space are particularly applicable to Equations (75) and (76) where the time interval considered in the equations has been shortened to days and weeks. Further, it is possible to qualitatively evaluate average rates of exchange during specified periods of the year. As an example, the parameter " RB " should be a maximum during the spring and fall turnover and should reduce to a minimum during the summer periods when thermal stratification tends to prevent exchange in an upward direction. " RL " would tend to follow the same pattern as " RB " during the summer period and overturns. In the winter, " RL " would tend to increase. For certain substances like PO_4 and organic matter, "RL " would increase during the early fall and late summer. The specific pattern of variation for the several parameters would vary depending on the substance being studied.

In consideration of local pollution situations, information on wind is of importance. In addition, it is necessary to evaluate the dispersion coefficient and its' variation with distance. The principal difference in data collection when considering local pollution is in the radial location of sampling stations required. These sampling locations are required to provide verification for the models and a limited number are illustrated on Figure 42.

NOMENCLATURE - STREAM AND ESTUARY

Computer	Other	Definition	Units
$\overline{A}$	-----	Chloride constants	mg/l
A(I)	A	Cross-sectional area	ft^2
AA(I)	-----	Average area for uniform loads in expanding area sections	ft^2
AK(I)	K_a K_2	Reaeration coefficient	1/day
AO(I)	Ao	Initial cross-sectional area for expanding area sections	ft^2
B(I)	B	BOD constant (B associated with S)	mg/l
BOD(I)	L	BOD Concentration	mg/l
BU(I)	B	Bottom oxygen demand	gm/M - day
$\overline{C}$	S	Concentration of conservative substance	mg/l
C(I)	C	BOD constant (C associated with V)	mg/l
DEF (I)	D	Deficit	mg/l
DK(I)	Kd	BOD oxidation coefficient	1/day
E(I)	E	Dispersion coefficient	mi^2/day

Computer	Other	Definition	Units
F(I)	f	Ultimate to 5-day BOD ratio	-----
G(I)	G	Deficit constant (G associated with SD)	mg/l
H(I)	H	Deficit constant (H associated with VD)	mg/l
HT(I)	h	Water depth	M (meters)
I, K, KK	-----	Section N^{o}	-----
J	-----	Boundary Equation N^{o}	-----
PA(I)	P	Algae oxygen production	mg/1 - day
Q(I)	Q	Flow	cfs
R(I,J)	R	Distance in spherical or cylinderical coordinate	mi
RA(I)	R	Algae respiration	mg/l - day
RK(I)	Kr	BOD removal coefficient	1/day
RO	Ro	Distance from origin for expanding area sections to location of Ao	mi
RP(I)	R - P	Algae influence (R - P)	mg/l - day
S(I)	g+	$\frac{U}{2E}\left[1+\left(1+\frac{4\cdot RK\cdot E}{U^2}\right)^{1/2}\right]$	(+) 1/mi
SD(I)	f+	Replacing RK by AK in above	(+) 1/mi

Computer	Other	Definition	Units
TEMP(I)	T	Temperature	$^\circ C$
TIDE(I)	R	Exchange coefficient	1/day
U(I)	U	Velocity (fresh water)	fps
V(I)	i-	$\frac{U}{2E}\left[1-\left(1+\frac{4\cdot RK\cdot E}{U^2}\right)^{1/2}\right]$	(-) 1/mi
VD(I)	h-	Replacing RK by AK in above	(-) 1/mi
VOL(I)	Vol	Volume	ft^3
W(J)	W	Point waste input	lbs/day
WU(I)	W	Uniform waste input	lbs/day - mi
XA(I,2)	-----	Location of upstream boundary for section	mi
XA(I,J)	X	Distance in rectangular coordinate	mi
XA(I,1),XY XZ,XX	a,b,c, et al	Location of downstream boundary for section	mi
YB(I)	-----	Particular integral BOD	mg/l
YD(X,I)	P	Particular integral DEF	mg/l

Computer	Other	Definition	Units
Functions			
fa(X,I)	-----	Expanding DEF	-----
$\overline{\text{fa}}$(X,I)	-----	Decreasing DEF	-----
fr(X,I)	-----	Expanding BOD	-----
$\overline{\text{fr}}$(X,I)	-----	Decreasing BOD	-----

Note: ALL DERIVATIVES ARE INDICATED BY PRIME MARKS

Bessell functions

Iv(GaR)		Expanding DEF	
Iv(GrR)		Expanding BOD	
Kv(GaR)		Decreasing DEF	
Kv(GrR)		Decreasing BOD	

Note: MODIFIED BESSEL FUNCTIONS OF THE FIRST AND SECOND KIND

NOMENCLATURE - LAKE MODELS

Parameter		Symbol	Units
Lake volume		VL	ft^3
Bottom volume		VB	ft^3
Top layer volume		VT	ft^3
Bottom layer volume		VB	ft^3
Reaction rates	Lake	KL	1/day
	Bottom	KB	1/day
	Top layer	KT	1/day
	Bottom layer	KB	1/day
Exchange rates	Lake	RL	1/day
	Bottom	RB	1/day
	Top layer	RT	1/day
	Bottom layer	RB	1/day
Flow		Q	ft^3/ day
Flow average		Q	
Waste inputs (total of all sources)		WL	#/ day OR #/ year
Concentrations	Lake	C_L	mg / l
	Bottom	C_B	mg / l
	Top layer	C_T	mg / l
	Bottom layer	C_B	mg / l
Time - space average	Lake	$\bar{C}_L$	mg / l
	Bottom	$\bar{C}_B$	mg / l
	Top Layer	$\bar{C}_T$	mg / l
	Bottom layer	$\bar{C}_B$	mg / l
Average leaving lake		$\bar{\bar{C}}_L$	mg / l
Constants evaluated by boundary conditions		ML, NL,	mg / l
		MB, NB,	mg / l
		BB, AB,	mg / l
		BT, AT,	mg / l
		C, B, A,	mg / l
		M	mg / l

NOMENCLATURE - LAKE MODELS

Parameter	Symbol	Units
Initial concentration	Co	ppm
Dispersion coefficient	E	ft^2 / day
Initial dispersion coefficient	Eo	ft^2 / day
Distances	X Y	ft ft
Velocity	R U	ft ft
Initial width of field	W	ft
Error function	Erf	
Heat transfer coefficient	θ	BTU / day - ft^2
Temperature	T	°C
Time	t	day years
Frequency	a	- - -
Period	p	- - -

APPENDIX A

```
CF    PROGRAM KAPPY
     0DIMENSION AM(1,1),BFORC(1),AREA(1),E(1),AK(1),RK(1),DK(1),F(1),Q(1
     4),S(1),V(1)
     0DIMENSION SD(1),VD(1),VEL(1),DEFD(1),TEMP(1),FAC(1),B(1),C(1),DEF(
     41),X(1),BODD(1),BODU(1)
      COMMON AM,ZS,ZSD,ZV,ZVD,ZFAC,IROW,BFORC,B,C
      MTIMES=1
CF    READ 0,MROW
  153 CONTINUE
CF    READ 0,KROW
CF    READ 0,(E(I),AK(I),RK(I),F(I),DK(I),TEMP(I),I=1,KROW)
CF    READ 0,IROW,WA,WB,WC,DA,DB,DC
CF    READ 0,XY,XZ,FA,FB,FC
CF    READ 0,(AREA(I),Q(I),I=1,KROW)
      DO 11 I=1,KROW
      AREA(I)=AREA(I)/5280.**2
      Q(I)=Q(I)*3600.*24./5280.**3
      VEL(I)=Q(I)/AREA(I)
   11 CONTINUE
      DO 10 I=1,KROW
      AK(I)=AK(I)*1.02**(TEMP(I)-20.)
      DK(I)=DK(I)*1.04**(TEMP(I)-20.)
      RK(I)=RK(I)*1.04**(TEMP(I)-20.)
      CALL HROT(E(I),VEL(I),AK(I),RK(I),F(I),DK(I))
      S(I)=ZS
      V(I)=ZV
      SD(I)=ZSD
      VD(I)=ZVD
   10 FAC(I)=ZFAC
      PRINT 20,(S(I),SD(I),V(I),VD(I),FAC(I),I=1,KROW)
   20 FORMAT(36H   S     SD       V      VD      FAC,/,(5F7.4))
      DO 1 KK=1,IROW
      BFORC(KK)=0.
      DO 1 LL=1,IROW
    1 AM(KK,LL)=0.
      ZW=10.**6/(62.4*5280.**3)
      WA=FA*WA*ZW
      WB=FB*WB*ZW
      WC=FC*WC*ZW
      DA=DA*ZW
      DB=DB*ZW
      DC=DC*ZW
      AM(1,1)=EXP(S(1)*XY)
      AM(2,1)=(E(1)*AREA(1)*S(1)-Q(1))*AM(1,1)
      AM(1,2)=-(EXP(S(2)*XY))
      AM(2,2)=(Q(2)-E(2)*AREA(2)*S(2))*(-1.)*AM(1,2)
      AM(3,2)=1.
      AM(4,2)=E(2)*AREA(2)*S(2)-Q(2)
      AM(1,3)=-(EXP(V(2)*XY))
      AM(2,3)=(Q(2)-E(2)*AREA(2)*V(2))*(-1.)*AM(1,3)
      AM(3,3)=1.
      AM(4,3)=E(2)*AREA(2)*V(2)-Q(2)
      AM(3,4)=-1.
      AM(4,4)=Q(3)-E(3)*AREA(3)*S(3)
      AM(6,4)=EXP(S(3)*XZ)
      AM(5,4)=(E(3)*AREA(3)*S(3)-Q(3))*AM(6,4)
      AM(3,5)=-1.
      AM(4,5)=Q(3)-E(3)*AREA(3)*V(3)
      AM(6,5)=EXP(V(3)*XZ)
      AM(5,5)=AM(6,5)*(-(AM(4,5)))
      AM(6,6)=-(EXP(V(4)*XZ))
      AM(5,6)=(Q(4)-E(4)*AREA(4)*V(4))*(-1.)*AM(6,6)
      BFORC(2)=WC
      BFORC(4)=WB
      BFORC(5)=WA
      IERR=1
      Z=1.
      CALL SIMULT(IROW,Z)
      PRINT 199,(C(II),II=1,IROW)
  199 FORMAT(10F10.3)
      DO 70 J=2,50,5
      X(J)=2-J
      IF(X(J)-XY)72,73,73
   72 BODU(J)=C(1)*EXP(S(1)*X(J))
      GO TO 74
   73 BODU(J)=C(2)*EXP(S(2)*X(J))+C(3)*EXP(V(2)*X(J))
   74 X(J)=-(X(J))
      IF(X(J)-XZ)75,75,76
   75 BODD(J)=C(4)*EXP(S(3)*X(J))+C(5)*EXP(V(3)*X(J))
      GO TO 70
   76 BODD(J)=C(6)*EXP(V(4)*X(J))
   70 CONTINUE
      PRINT 78,(BODD(JL),BODU(JL),X(JL),JL=2,50,5)
   78 FORMAT(6H  BODD6H  BODU3H  X/(2F6.2,F4.0))
      DO 2 KK=1,IROW
      BFORC(KK)=0.
      DO 2 LL=1,IROW
    2 AM(KK,LL)=0.
      AM(1,1)=EXP(SD(1)*XY)
      AM(2,1)=(E(1)*AREA(1)*SD(1)-Q(1))*AM(1,1)
      AM(1,2)=-(EXP(SD(2)*XY))
      AM(2,2)=(-1.)*AM(1,2)*(Q(2)-E(2)*AREA(2)*SD(2))
      AM(3,2)=1.
      AM(4,2)=E(2)*AREA(2)*SD(2)-Q(2)
      AM(1,3)=-(EXP(VD(2)*XY))
      AM(2,3)=(Q(2)-E(2)*AREA(2)*VD(2))*(-1.)*AM(1,3)
      AM(3,3)=1.
      AM(4,3)=E(2)*AREA(2)*VD(2)-Q(2)
      AM(3,4)=-1.
      AM(4,4)=Q(3)-E(3)*AREA(3)*SD(3)
      AM(5,4)=EXP(SD(3)*XZ)
      AM(6,4)=-(AM(4,4)*AM(5,4))
      AM(3,5)=-1.
      AM(4,5)=Q(3)-E(3)*AREA(3)*VD(3)
      AM(5,5)=EXP(VD(3)*XZ)
      AM(6,5)=AM(5,5)*(E(3)*AREA(3)*VD(3)-Q(3))
      AM(5,6)=-(EXP(VD(4)*XZ))
      AM(6,6)=AM(5,6)*(Q(4)-E(4)*AREA(4)*VD(4))*(-1.)
      Z2=C(2)*EXP(S(2)*XY)
      Z3=C(3)*EXP(V(2)*XY)
      Z1=C(1)*EXP(S(1)*XY)
      Z6=C(6)*EXP(V(4)*XZ)
      Z5=C(5)*EXP(V(3)*XZ)
      Z4=C(4)*EXP(S(3)*XZ)
      BFORC(1)=FAC(2)*(Z2+Z3)-FAC(1)*Z1
     0BFORC(2)=E(2)*AREA(2)*FAC(2)*(S(2)*Z2+V(2)*Z3)+FAC(1)*Z1*(Q(1)-E(1
     4)*AREA(1)*S(1))-Q(2)*FAC(2)*Z3+DC
      BFORC(2)=BFORC(2)-Q(2)*FAC(2)*Z2
      BFORC(3)=FAC(3)*(C(4)+C(5))-FAC(2)*(C(2)+C(3))
      FART1=FAC(2)*Q(2)*(C(2)+C(3))
      FART2=E(2)*AREA(2)*FAC(2)*(C(2)*S(2)+C(3)*V(2))
      FART3=Q(3)*FAC(3)*(C(4)+C(5))
      FART4=E(3)*AREA(3)*FAC(3)*(C(4)*S(3)+C(5)*V(3))+DB
      BFORC(4)=FART1-FART2-FART3+FART4
      BFORC(5)=FAC(4)*Z6-FAC(3)*(Z4+Z5)
     0BFORC(6)=FAC(3)*Q(3)*(Z4+Z5)-E(3)*AREA(3)*FAC(3)*(S(3)*Z4+V(3)*Z5)
     4+FAC(4)*Z6*(E(4)*AREA(4)*C(6)-Q(4))+DA
      BFORC(6)=BFORC(6)+FAC(4)*Z6*E(4)*AREA(4)*(V(4)-C(6))
      Z=0
      CALL SIMULT(IROW,Z)
      PRINT 199,(B(II),II=1,IROW)
      DO 50 J=2,50,5
      X(J)=2-J
      IF(X(J)-XY)62,63,63
   62 DEF(J)=B(1)*EXP(SD(1)*X(J))+FAC(1)*C(1)*EXP(S(1)*X(J))
      GO TO 64
   630DEF(J)=B(2)*EXP(SD(2)*X(J))+B(3)+FAC(2)*(C(2)*EXP(S(2)*X(J))+C(3)*
     4EXP(V(2)*X(J)))+B(3)*(-1.+EXP(VD(2)*X(J)))
   64 X(J)=-(X(J))
      IF(X(J)-XZ)65,65,66
   650DEFD(J)=B(4)*EXP(SD(3)*X(J))+B(5)+FAC(3)*(C(4)*EXP(S(3)*X(J))+C(5)
     4*EXP(V(3)*X(J)))+B(5)*(-1.+EXP(VD(3)*X(J)))
      GO TO 50
   66 DEFD(J)=B(6)*EXP(VD(4)*X(J))+FAC(4)*C(6)*EXP(V(4)*X(J))
   50 CONTINUE
      PRINT 68,(DEFD(J),DEF(J),X(J),J=2,50,5)
   68 FORMAT(6H  DEFD6H  DEFU3H  X/(2F6.2,F4.0))
      IF(MTIMES-MROW)155,154,154
  155 MTIMES=MTIMES+1
      GO TO 153
  154 STOP 1066
      END
      SUBROUTINE SIMULT(M,Z)
      DIMENSION AM(8,8),BFORC(8),B(8),C(8),AMM(8,9)
      COMMON AM,ZS,ZSD,ZV,ZVD,ZFAC,IROW,BFORC,B,C
      DO 12 I=1,M
      IF(AM(I,I))12,13,12
   13 PRINT 14
   140FORMAT(82H0THERE IS A ZERO ELEMENT ON THE MAIN DIAGONAL OF YOUR COF
     4EFFICIENT MATRIX. YOU LOSE.)
      STOP 1065
   12 CONTINUE
      N=M+1
      DO 6 I=1,M
      DO 6 J=1,M
    6 AMM(I,J)=AM(I,J)
      DO 7 I=1,M
    7 AMM(I,N)=BFORC(I)
      KPASS=0
      DO 3 IHOT=1,M
      KPASS=KPASS+1
      TT=AMM(IHOT,IHOT)
      DO 2 L=IHOT,N
    2 AMM(IHOT,L)=AMM(IHOT,L)/TT
      DO 3 II=1,M
      IF(II-KPASS)4,3,4
    4 T=AMM(II,KPASS)
      DO 5 LL=1,N
    5 AMM(II,LL)=AMM(IHOT,IHOT)*AMM(II,LL)-T*AMM(KPASS,LL)
    3 CONTINUE
      IF(Z)10,11,10
   10 DO 21 I=1,M
   21 C(I)=0.
      DO 20 I=1,M
   20 C(I)=C(I)+AMM(I,N)
      GO TO 40
   11 DO 23 I=1,M
   23 B(I)=0.
      DO 22 I=1,M
   22 B(I)=B(I)+AMM(I,N)
   40 RETURN
      END
      PROGRAM UPMUD
      DIMENSION DEF(50),BOD(50),RR(50),FOFR(50)
      REAL JA,JR,M
      K=1
      READ 0,DEFO,BODO,ITSEC
    1  CONTINUE
      R=0.
      READ 0, AK,DK,RK,W,Q0,Q1,RDEL,RTOT,M,AO,F,TEMP
      W=W/5.4
      Q=Q0+Q1
      DEF1=(Q0*DEFO)/Q
      BOD1=(Q0*BODO+W)/Q
      AK=AK*1.02**(TEMP-20.)
      DK=DK*1.04**(TEMP-20.)
      RK=RK*1.04**(TEMP-20.)
      I=1
      RO=AO/M
      JA=-(AK*M/Q/16.4)
      JR=-(RK*M/Q/16.4)
    2 FOFR(I)=(R*R+2.*R*RO)/2.
      RJA=JA*FOFR(I)
      RJR=JR*FOFR(I)
      TERM1=F*DK*BOD1/(AK-RK)*(EXP(RJR)-EXP(RJA))
      TERM2=DEF1*EXP(RJA)
      DEF(I)=TERM1+TERM2
      BOD(I)=BOD1*EXP(RJR)
      RR(I)=R
      IF(R-RTOT)3,4,4
    3 R=R+RDEL
      I=I+1
      GO TO 2
    4 DEFO=DEF(I)
      BODO=BOD(I)
      PRINT 5,K
    5 FORMAT(7HSEGMENTI2)
      K=K+1
      PRINT 6
    6 FORMAT(8X,1HR,8X,3HDEF,8X,3HBOD)
      PRINT7,(RR(J),DEF(J),BOD(J),J=1,I)
    7 FORMAT(F11.2,F10.2,F11.2)
      IF(K-ITSEC)2,2,8
    8 STOP 55555
      END
```

APPENDIX B

1959 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N 1	36.7	69.5	5.05	60.7	1.32
July		41.5	72.8	5.00	61.3	1.28
August		48.1	75.1	3.37	47.5	1.15
Sept.		51.0	73.9	3.43	43.5	1.06
June	N 2	41.8	69.5	4.53	54.3	1.48
July		41.5	73.0	5.53	68.3	1.90
August		50.3	75.5	3.71	47.6	1.04
Sept.		55.8	73.9	3.10	39.8	1.25
June	N 3	45.2	68.8	4.02	47.7	1.62
July		48.0	72.5	4.58	57.8	1.23
August		53.6	74.6	3.10	40.0	0.93
Sept.		61.8	64.9	2.58	33.5	1.28
June	N 3a	54.3	68.0	3.67	44.0	1.62
July		57.8	72.3	4.13	52.0	1.60
August		60.0	74.5	2.70	35.0	1.30
Sept.		69.3	73.3	2.06	26.6	1.33
June	N 3b	48.0	69.2	4.02	43.9	1.40
July		54.0	72.2	3.37	42.3	1.78
August		57.8	74.8	3.11	40.3	1.10
Sept.		64.0	73.6	2.45	31.6	1.63

1959 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N 4	57.0	68.3	3.50	42.2	1.97
July		61.5	72.2	3.68	46.8	1.43
August		71.0	74.0	2.28	30.0	1.28
Sept.		71.0	68.4	2.25	29.4	1.56
June	N 5	71.8	66.7	3.57	43.5	1.90
July		74.0	70.5	3.55	45.5	1.23
August		75.3	73.0	2.05	26.6	1.07
Sept.		79.9	72.0	2.63	34.5	1.22
June	N 6	73.2	65.6	4.26	50.4	3.26
July		76.4	73.7	3.01	39.4	2.06
August		79.6	80.2	2.35	31.3	2.47
Sept.		80.7	68.2	2.83	3.63	3.16
June	N 7	72.8	64.8	4.44	51.7	2.59
July		77.2	72.4	2.85	37.4	1.38
August		80.1	72.4	2.49	32.9	1.24
Sept.		82.0	67.2	2.82	35.5	2.61
June	N 8	78.4	67.8	5.30	65.1	2.94
July		84.3	72.0	3.83	50.3	1.00
August		83.0	73.4	3.07	41.4	1.28
Sept		84.5	66.8	3.87	48.8	1.38
June	N 9	92.0	63.5	7.48	92.8	3.42
July		93.0	68.3	6.67	86.5	0.98
August		93.3	70.8	5.00	67.1	0.78
Sept.		92.4	66.2	5.78	73.7	1.22
June	N 9a	93.0	62.5	7.53	92.3	1.57
July		94.7	67.5	6.78	87.7	0.98
August		92.4	72.2	5.70	77.3	1.17
Sept.		92.7	65.5	5.75	72.5	2.50
June	N 16	96.0	63.5	7.45	92.5	1.40
July		96.3	66.3	7.83	100.7	0.83
August		97.1	69.8	6.82	91.0	0.73
Sept.		98.5	63.7	6.05	91.4	0.91

1960 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		31.0	69.0	4.41	50.4	0.94
July	N	42.0	74.0	3.95	49.6	1.18
August	1	35.8	75.7	4.04	50.7	1.66
Sept.		--	--	--	--	--
June		36.0	66.5	3.68	43.0	0.84
July	N	47.0	74.0	3.90	49.2	1.39
August	2	37.3	75.2	3.68	47.2	1.24
Sept.		--	--	--	--	--
June		40.0	68.3	3.78	44.3	1.28
July	N	55.0	73.0	2.98	37.8	1.34
August	3	46.9	75.0	2.95	37.3	1.88
Sept.		--	--	--	--	--
June		53.9	67.4	3.28	39.1	2.00
July	N	62.5	72.3	2.78	35.6	1.90
August	3a	52.3	74.6	2.75	36.4	2.09
Sept.		--	--	--	--	--
June		42.4	68.3	3.55	41.5	1.30
July	N	59.3	73.0	3.28	41.8	1.46
August	3b	45.0	74.8	3.44	41.5	1.31
Sept.		--	--	--	--	--

1960 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N 4	53.4	67.4	2.95	35.4	2.15
July		66.3	72.5	2.60	33.5	1.68
August		54.2	74.6	2.52	32.3	1.73
Sept.		--	--	--	--	--
June	N 5	68.8	66.4	3.45	41.8	1.26
July		78.0	70.5	2.98	38.4	1.38
August		68.8	73.1	2.50	31.6	1.18
Sept.		--	--	--	--	--
June	N 6	69.0	67.1	3.67	44.8	2.39
July		79.0	69.8	3.42	33.8	2.58
August		71.6	72.9	2.65	34.7	2.27
Sept.		79.3	72.6	2.83	37.0	2.60
June	N 7	71.0	66.7	3.65	47.4	1.62
July		79.0	69.4	3.28	42.2	1.68
August		71.2	72.6	2.84	45.2	1.58
Sept.		77.5	72.3	2.61	38.2	1.26
June	N 8	77.0	67.1	5.06	60.3	1.82
July		83.8	70.0	4.70	61.3	1.45
August		76.3	72.3	3.81	46.7	1.53
Sept.		80.1	83.4	4.06	54.2	1.16

1960 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		87.4	65.3	7.10	87.4	1.24
July	N	98.0	68.6	7.23	95.4	1.13
August	9	93.8	71.0	6.04	80.9	1.68
Sept.		92.0	72.5	5.88	79.5	1.43
June		91.8	66.1	7.39	91.8	1.84
July	N	92.5	69.6	7.18	94.7	2.78
August	9a	90.1	71.6	6.51	87.2	2.18
Sept.		88.5	72.5	6.70	90.2	2.85
June		95.9	63.3	7.73	94.8	1.40
July	N	98.8	66.7	7.60	98.5	1.66
August	16	94.6	71.1	7.25	97.4	1.52
Sept.		93.3	70.5	6.60	88.2	1.20

1961 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N 1	24.8	67.8	5.27	69.2	1.20
July		38.0	73.7	4.93	60.7	1.37
August		39.4	78.0	3.52	44.8	.67
Sept.		--	--	--	--	--
June	N 2	29.0	67.3	5.18	68.5	0.60
July		36.4	67.8	4.20	52.0	1.23
August		46.2	77.5	3.32	45.1	.85
Sept.		--	--	--	--	--
June	N 3	45.8	66.2	5.20	60.3	2.35
July		43.5	73.0	3.68	45.8	.75
August		57.7	76.8	2.56	59.0	.45
Sept.		--	--	--	--	--
June	N 3a	44.0	67.5	6.18	60.8	1.80
July		53.7	72.5	3.07	38.2	1.82
August		60.0	76.6	2.48	33.0	1.58
Sept.		--	--	--	--	--
June	N 3b	39.8	66.3	5.23	60.0	1.35
July		45.8	73.0	3.70	46.2	.93
August		53.4	77.1	2.62	34.7	1.73
Sept.		--	--	--	--	--

1961 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_4	49.7	65.0	5.05	58.2	2.30
July		55.3	71.8	3.03	38.2	1.78
August		62.4	76.6	2.30	30.6	2.32
Sept.						
June	N_5	63.2	63.0	4.57	52.3	1.95
July		68.2	70.8	3.73	46.3	1.32
August		77.0	74.9	2.39	32.0	1.70
Sept.						
June	N_6	67.9	62.8	4.73	55.8	2.65
July		74.4	70.7	4.27	54.9	1.45
August		73.1	74.1	2.66	35.3	1.89
Sept.		73.6	75.5	2.66	36.1	1.40
June	N_7	67.2	62.4	4.59	53.5	2.50
July		70.6	70.4	3.92	50.2	1.68
August		70.6	73.9	2.52	25.9	1.33
Sept.		73.6	71.1	2.84	38.1	.98
June	N_8	73.4	73.4	5.24	62.0	2.42
July		7.70	81.1	5.32	69.2	.60
August		81.7	73.7	4.17	54.3	1.46
Sept.		79.1	76.5	3.58	48.5	.85

1961 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		89.4	60.3	7.71	92.0	1.50
July	N 9	93.2	68.5	7.12	91.2	2.38
August		95.3	71.0	6.10	82.4	2.23
Sept.		89.0	73.3	5.53	74.8	.50
June		92.8	59.1	8.36	98.9	2.08
July	N 16	98.5	67.0	8.12	104.3	1.08
August		98.9	70.1	8.29	93.3	.83
Sept.		97.0	72.3	5.68	76.8	.70
June		70.1	63.5	4.56	53.9	2.93
July	K 1	70.0	72.9	3.40	43.8	1.32
August		71.1	74.3	2.63	34.5	2.13
Sept.		76.0	75.3	2.68	36.3	2.20
June		58.6	67.3	4.41	53.1	3.50
July	K 2	63.4	75.3	3.25	42.0	2.08
August		62.8	76.3	2.25	33.4	1.67
Sept.		70.3	77.5	2.55	34.8	0.00
June		59.6	69.3	2.46	58.4	4.25
July	K 3	63.5	77.3	1.03	9.3	2.70
August		61.8	78.0	.80	5.1	3.35
Sept.		70.3	78.0	1.95	2.68	0.00

1962 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N 1	40.5	71.7	3.88	47.1	0.65
July		52.0	73.7	4.05	51.0	1.60
August		58.7	75.0	3.77	48.6	1.95
Sept.		50.1	72.5	3.50	47.4	
June	N 2	50.2	71.0	3.32	42.4	.53
July		52.8	73.7	3.60	45.4	1.40
August		59.1	75.3	3.31	43.9	1.07
Sept.		54.5	73.0	2.55	32.1	
June	N 3	51.7	69.5	3.00	34.6	1.15
July		60.0	72.7	2.67	33.7	1.50
August		61.6	74.5	2.99	38.9	.88
Sept.		59.5	71.5	2.25	43.2	
June	N 3b	51.2	69.7	2.68	32.2	1.75
July		54.8	72.8	2.90	36.7	1.80
August		65.0	74.8	2.72	34.5	1.45
Sept.		59.5	72.0	2.15	27.1	
June	N 4	62.8	68.8	2.21	27.2	1.95
July		62.0	72.7	2.48	30.2	2.13
August		74.2	74.3	2.59	34.7	1.20
Sept.		70.0	72.0	1.45	21.3	

1962 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_5	74.8	67.7	2.22	27.6	1.68
July		78.2	71.8	2.22	29.1	2.73
August		83.1	73.6	2.29	30.1	1.19
Sept.		80.5	73.0	1.45	19.3	
June	N_6	76.5	65.9	3.01	37.6	1.58
July		79.3	71.7	3.09	39.8	1.96
August		82.9	77.3	2.69	34.9	1.78
Sept.		75.8	71.3	2.48	31.5	1.18
June	N_7	73.9	65.8	3.06	36.2	1.03
July		80.4	71.6	3.06	40.9	1.74
August		83.5	72.7	2.46	32.6	1.48
Sept.		76.0	70.5	1.95	25.1	1.15
June	N_8	82.7	65.4	4.46	54.1	1.39
July		83.4	71.8	4.39	57.9	2.08
August		85.2	72.4	3.64	48.8	1.77
Sept.		85.3	71.0	3.31	41.5	1.53
June	N_9	94.5	62.3	6.90	85.2	1.03
July		90.6	71.3	5.66	74.5	1.59
August		95.4	69.5	5.63	74.2	.78
Sept.		94.0	68.0	4.90	63.6	1.05

1962 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_{9a}	92.5	62.8	7.02	86.6	2.70
July		90.9	72.4	5.83	78.5	2.78
August		95.9	70.9	6.19	83.1	1.84
Sept.		94.0	65.0	5.55	69.9	1.35
June	N_{16}	95.5	61.2	7.98	99.0	1.00
July		96.6	69.8	6.06	80.4	1.91
August		98.1	69.5	6.96	93.0	.58
Sept.		98.0	67.0	5.70	73.7	1.30
June	K_6	82.8	68.7	7.52	61.7	4.20
July		87.9	72.1	7.83	80.7	3.34
August		90.4	74.0	6.06	83.2	1.84
Sept.		89.0	73.5	4.25	57.8	2.10
June	N_{3a}	59.5	69.2	2.40	29.4	1.33
July		57.2	72.3	2.60	32.9	1.50
August		69.9	74.5	2.43	33.7	.88
Sept.		66.0	72.0	1.65	21.5	1.00

1963 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_1	40.3	69.0	4.38	52.0	1.68
July		51.1	75.8	4.44	58.4	1.78
August		52.5	75.1	4.01	51.6	1.46
Sept.		41.5	71.0	2.65		1.40
June	N_2	42.5	70.0	4.48	54.2	1.35
July		53.5	75.6	4.33	56.1	1.76
August		57.3	74.8	3.80	48.5	1.44
Sept.		59.7	71.0	5.40	66.3	1.55
June	N_3	49.0	60.5	5.43	40.9	1.74
July		55.9	74.6	4.04	52.1	2.30
August		60.9	74.0	3.38	43.2	1.49
Sept.		60.0	73.5	4.30	53.2	.85
June	N_{3a}	56.0	68.8	3.03	40.0	1.95
July		64.0	73.6	3.64	47.3	1.71
August		68.1	74.1	4.21	46.7	1.96
Sept.		63.0	70.5	2.85	35.8	1.25
June	N_{3b}	46.8	68.8	4.18	48.2	2.20
July		53.8	74.1	3.60	46.5	1.61
August		67.8	74.8	3.39	43.9	1.49
Sept.		59.0	70.5	3.70		1.45

1963 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_4	58.3	69.3	2.78	34.6	2.12
July		63.4	75.3	3.41	43.9	1.90
August		72.4	73.5	2.01	27.4	1.98
Sept.		66.5	70.5	2.00	25.6	1.00
June	N_5	70.5	67.3	2.23	27.8	1.98
July		80.8	80.4	2.95	39.0	1.96
August		78.4	71.9	2.94	35.2	1.78
Sept.		76.0	70.0	2.65	34.0	1.65
June	N_6	73.7	67.6	2.65	34.9	2.44
July		81.7	71.6	3.13	41.3	1.98
August		82.9	70.1	3.20	41.9	1.71
Sept.		84.4	68.7	3.55	45.6	1.79
June	N_7	75.9	67.1	2.82	35.0	2.50
July		79.9	70.7	3.33	44.2	2.93
August		82.8	70.3	3.16	41.0	2.02
Sept.		83.4	68.1	3.48	44.5	1.58
June	N_8	82.6	67.3	4.09	51.6	2.10
July		86.4	71.4	4.62	61.4	2.04
August		85.9	71.1	4.22	56.7	1.97
Sept.		85.8	70.1	4.15	54.2	1.81

1963 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_9	92.3	63.3	6.78	82.4	1.48
July		95.3	69.3	6.19	81.5	1.68
August		95.1	66.5	5.98	76.2	1.70
Sept.		95.5	66.5	6.33	74.4	1.25
June	N_{9a}	98.5	64.3	6.98	88.2	2.18
July		95.3	69.3	6.70	88.8	2.74
August		93.9	67.6	6.31	81.6	2.06
Sept.		93.8	66.5	6.90	89.9	2.15
June	N_{16}	100.0	61.5	7.60	94.3	1.90
July		95.8	67.9	6.89	89.6	2.00
August		97.3	64.0	6.35	79.7	1.69
Sept.		96.8	66.0	6.65	85.8	1.33
June	K_{5a}	73.2	70.8	4.88	63.6	4.70
July		82.3	75.5	4.41	59.4	4.26
August		84.8	74.4	4.71	57.4	6.53
Sept.		84.3	72.3	4.80	64.0	4.13
June	K_6	83.0	68.2	5.80	73.7	3.22
July		84.3	73.9	8.23	95.8	2.86
August		87.9	73.1	7.08	95.1	2.71
Sept.		91.3	71.0	6.70	89.1	2.00

1964 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_1	46.2	66.2	4.73	55.0	3.85
July		45.6	74.3	4.46	60.2	3.39
August		49.8	73.6	4.23	51.9	4.49
Sept.		46.5	72.5	4.15	51.5	----
June	N_2	54.5	66.7	3.95	46.1	4.63
July		49.4	74.1	4.45	56.5	3.39
August		54.5	73.4	4.06	40.6	4.09
Sept.		57.5	72.5	3.65	55.9	----
June	N_3	55.2	65.6	3.65	42.8	3.35
July		54.4	73.6	3.94	50.2	3.14
August		61.3	73.1	2.98	38.1	3.89
Sept.		63.0	72.0	4.70	59.7	----
June	N_{3a}	60.5	64.7	3.73	43.9	1.98
July		60.5	73.0	3.40	43.5	3.60
August		66.3	72.6	3.18	40.6	4.34
Sept.		68.0	71.5	4.30	59.4	----
June	N_{3b}	59.8	65.2	3.73	43.6	2.80
July		54.9	74.0	3.85	49.4	2.90
August		56.1	72.8	2.88	37.0	4.02
Sept.		64.5	72.5	3.60	46.2	----

1964 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_4	64.5	67.0	4.78	60.7	2.72
July		64.3	72.3	2.71	34.8	3.06
August		69.0	73.2	2.47	32.1	4.43
Sept.		70.5	71.5	3.15	40.5	----
June	N_5	76.8	65.2	8.75	109.6	2.27
July		74.3	70.8	2.49	31.7	3.51
August		76.0	71.8	2.73	35.7	3.93
Sept.		80.0	71.5	4.80	62.8	----
June	N_{9a}	91.8	62.3	7.68	94.0	3.64
July		89.5	70.1	6.85	90.2	4.43
August		93.1	68.3	6.76	87.6	3.24
Sept.		90.0	71.5	6.20	82.9	2.95
June	N_{16}	98.3	59.5	7.35	89.0	2.96
July		94.1	68.0	7.51	97.1	3.35
August		94.9	66.6	6.86	88.0	3.71
Sept.		97.0	70.0	7.25	96.5	3.25
June	H_1	44.7	66.5	4.21	49.1	2.38
July		54.2	66.0	3.27	41.5	3.18
August		54.4	72.7	3.47	43.5	3.81
Sept.		52.8	73.0	4.03	50.9	2.48

1965 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N_1	40.1	68.7	5.73	67.68	1.35
July		44.6	73.6	4.52	56.64	1.65
August		46.3	75.6	4.00	54.84	1.18
June	N_2	44.0	68.3	5.37	63.81	1.82
July		49.7	73.6	3.98	50.31	1.64
August		49.5	76.8	3.25	41.73	1.01
June	N_3	50.3	67.5	4.25	50.45	1.58
July		55.5	72.9	3.18	39.80	1.67
August		57.1	74.8	2.50	31.78	1.15
June	N_{3a}	57.0	68.2	3.73	44.43	1.93
July		60.6	72.1	2.95	37.49	2.23
August		66.6	74.5	2.21	28.48	1.22
June	N_{3b}	53.2	66.8	4.87	57.62	1.80
July		54.8	72.8	2.92	36.82	2.42
August		61.5	74.3	2.28	26.98	1.68
June	N_4	64.5	66.2	3.45	41.28	1.97
July		63.5	71.9	2.70	34.39	2.13
August		66.6	74.0	2.18	26.18	2.16

1965 SUMMARY

NORTH RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	N 5	75.0	63.6	3.93	47.02	1.90
July		75.8	70.4	2.75	35.53	2.76
August		79.4	72.8	2.66	35.44	1.38
June	N 6	79.8	65.2	3.85	47.05	2.36
July		82.6	70.3	2.88	40.43	2.22
August		83.4	71.7	2.92	40.46	1.94
Sept.		75.7	69.8	3.80	48.63	1.92
June	N 7	78.5	65.2	3.81	48.10	1.47
July		83.5	70.2	3.44	44.55	1.58
August		79.4	73.1	2.94	37.81	1.89
Sept.		71.7	69.7	3.32	41.85	4.43
June	N 8	81.0	64.3	4.60	58.10	1.83
July		85.3	69.8	4.14	53.6	1.66
August		84.2	73.0	3.56	47.6	1.85
Sept.		82.7	69.5	4.60	59.4	1.72
June	N 9	90.5	60.3	6.39	76.23	1.23
July		88.2	67.0	6.61	83.88	1.35
August		90.9	71.2	5.88	78.24	1.60
June	N 9a	90.1	63.1	6.37	78.03	2.20
July		87.0	67.7	6.77	87.31	1.87
August		89.5	72.1	6.19	82.98	1.90
June	N 16	94.3	60.0	7.03	84.43	1.27
July		90.6	65.8	6.62	85.58	1.30
August		82.5	71.2	6.61	88.54	1.39

EAST RIVER

1954 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm		Top and Bottom Averages		
		top	bottom	top & bottom	top	bottom	top	bottom	% Sea	D. O.	BOD
E_1	1	59	64	61	4.6	3.8	1.6	1.0	61.5	4.2	1.3
	2	77	78	70	2.4	2.4	1.6	1.3	77.5	2.4	1.45
	3	80	83	73	1.6	1.2	1.4	1.4	81.5	1.4	1.4
	4	78	79	70	2.1	2.1	1.4	1.7	78.5	2.1	1.55
E_2	1	66	70	63	3.5	3.8	2.4	1.6	68	3.65	2.0
	2	74	77	69	2.1	2.2	1.9	1.5	75.5	2.15	1.7
	3	80	82	72	1.2	1.2	1.8	1.5	81	1.2	1.65
	4	77	77	70	1.7	1.8	1.8	1.6	77	1.75	1.7
E_3	1	68	67	62	3.8	4.0	2.2	1.8	67.5	3.9	2.0
	2	75	77	69	2.4	2.4	2.6	1.7	76.0	2.4	2.15
	3	80	82	73	1.2	1.4	1.9	1.5	81	1.3	1.7
	4	78	79	70	1.6	1.7	2.2	1.2	78.5	1.65	1.7
E_4	1	69	69	62	2.8	2.8	1.8	2.4	69	2.8	2.1
	2	77	78	69	2.0	2.0	1.8	1.3	77.5	2.0	1.55
	3	83	84	72	0.8	1.0	1.5	1.2	83.5	0.9	1.35
	4	73	73	68	2.2	2.1	1.2	1.6	73	2.15	1.4
E_5	1	73	73	62	2.6	2.7	1.6	2.0	73	2.65	1.8
	2	77	80	69	2.3	2.4	1.6	1.3	78.5	2.35	1.45
	3	85	85	72	2.0	2.0	1.8	1.0	85	2.0	1.4
	4	75	75	68	2.2	1.4	1.4	1.1	75	1.8	1.25

EAST RIVER

1954 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm		Top and Bottom Averages		
		top	bottom	top & bottom	top	bottom	top	bottom	% Sea	D.O.	BOD
E_6	1	73	77	62	3.3	3.7	1.9	1.6	75	3.5	1.75
	2	79	80	69	2.8	2.5	1.6	1.4	79.5	2.65	1.5
	3	84	85	72	1.8	1.4	1.2	0.9	84.5	1.6	1.05
	4	80	77	68	2.6	1.2	1.2	1.4	78.5	1.9	1.3
E_7	1	75	76	60	4.9	4.9	2.0	1.5	75.5	4.9	1.75
	2	81	82	68	3.7	3.7	1.4	1.0	81.5	3.7	1.2
	3	85	87	72	3.1	3.1	1.0	0.8	86	3.1	0.9
	4	77	79	68	3.2	0.8	0.8	0.8	78	2.0	0.8
E_8	1	81	80	60	5.4	5.5	1.4	1.9	80.5	5.45	1.65
	2	82	83	68	4.2	4.3	1.5	1.7	82.5	4.25	1.6
	3	85	88	72	3.7	3.8	1.2	0.8	86.5	3.75	1.0
	4	81	81	68	3.8	4.6	0.9	0.6	81	4.2	0.75
E_9	1	80	78	60	7.0	7.0	2.0	1.6	79	7.0	1.8
	2	82	83	68	4.2	4.3	1.5	1.7	82.5	4.25	1.6
	3	85	88	72	3.7	3.9	1.2	0.8	86.5	3.75	1.0
	4	81	81	68	3.8	4.6	0.9	0.6	81	4.2	0.75
E_{10}	1	80	75	60	7.5	7.8	2.5	1.9	77.6	7.65	2.2
	2	84	86	67	5.7	5.5	1.8	1.3	85	5.6	1.55
	3	87	88	72	4.8	4.3	1.4	1.2	87.5	4.55	1.3
	4	83	81	68	5.9	6.0	0.9	0.7	82	5.95	0.8

EAST RIVER

1955 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_1	1	75	78	65	2.4	2.5	2.0	1.7
	2	79	81	72	2.1	2.2	2.0	1.3
	3	69	73	75	1.6	1.4	2.5	1.8
	4	73	74	71	2.2	2.7	1.8	1.6
E_2	1	74	76	65	1.9	2.0	2.2	1.7
	2	79	79	72	1.7	1.6	2.3	1.5
	3	73	75	75	1.0	1.2	2.6	1.6
	4	72	72	71	1.4	1.4	2.7	1.7
E_3	1	75	76	66	1.8	2.0	2.2	1.8
	2	80	81	72	1.5	1.7	2.6	1.7
	3	74	76	75	0.9	1.3	3.2	2.0
	4	74	73	71	1.4	1.4	3.8	1.8
E_4	1	80	82	66	2.8	3.0	2.3	1.3
	2	77	80	73	1.6	1.7	3.3	3.1
	3	75	76	76	1.1	1.3	2.7	2.0
	4	81	76	70	1.2	1.4	2.7	1.8
E_5	1	82	84	66	3.5	3.6	1.6	2.0
	2	82	83	73	1.9	1.9	2.3	1.3
	3	78	78	75	1.4	1.6	2.3	1.4
	4	80	80	69	2.6	2.6	1.0	1.0

EAST RIVER

1955 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_6	1	79	85	66	3.2	4.6	1.8	1.0
	2	82	83	72	1.6	1.8	2.3	1.5
	3	78	79	74	1.8	2.0	2.2	1.5
	4	78	80	69	2.6	3.0	1.2	0.8
E_7	1	83	84	65	4.9	5.4	2.1	1.2
	2	85	87	71	3.0	3.1	2.2	1.4
	3	82	82	75	2.6	3.0	2.0	1.0
	4	80	80	69	3.7	3.9	1.1	0.7
E_8	1	80	86	65	5.2	5.6	3.4	1.8
	2	84	85	69	3.7	3.8	1.9	1.2
	3	83	83	74	4.0	3.7	2.6	1.1
	4	80	80	69	3.9	3.9	0.7	0.2
E_9	1	82	86	68	7.3	7.8	2.8	1.1
	2	85	88	69	7.1	5.0	4.0	1.4
	3	84	86	73	4.4	4.5	3.2	1.1
	4	81	80	70	3.9	3.9	1.0	0.5
E_{10}	1	82	88	66	7.6	5.6	3.4	1.3
	2	85	88	69	6.4	4.9	2.8	1.4
	3	84	84	73	4.8	4.9	1.8	1.2
	4	81	80	70	4.3	4.2	1.0	0.5

EAST RIVER

1956 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_1	1	66	68	66	4.0	4.0	2.8	2.8
	2	70	71	69	2.1	2.3	2.3	1.8
	3	77	78	73	1.8	2.0	2.9	1.6
	4	72	76	69	2.2	2.3	3.2	1.5
E_2	1	68	79	65	4.4	3.8	5.4	3.2
	2	71	71	69	1.6	1.8	3.2	1.9
	3	76	77	73	1.2	1.8	3.3	1.7
	4	73	74	69	1.7	1.8	3.8	1.6
E_3	1	76	70	65	4.4	4.4	4.6	3.0
	2	72	73	69	1.4	1.5	4.6	2.7
	3	76	76	73	1.3	1.3	5.4	2.1
	4	74	74	69	1.8	2.0	4.9	2.0
E_4	1	71	72	66	3.6	3.9	3.8	4.5
	2	72	72	69	2.1	2.1	2.1	1.7
	3	78	80	72	1.4	1.6	4.4	3.7
	4	75	75	74	1.0	1.4	5.0	3.9
E_5	1	70	75	64	5.3	5.8	3.4	1.5
	2	74	75	69	1.6	2.1	2.1	1.3
	3	78	81	71	1.8	1.9	3.4	3.2
	4	79	80	74	1.2	1.4	4.3	3.5

EAST RIVER

1956 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_6	1	72	77	62	4.5	6.4	2.6	1.8
	2	75	76	68	2.0	2.5	1.9	1.4
	3	79	82	71	1.5	2.0	3.8	3.3
	4	83	82	73	1.9	2.0	4.5	5.1
E_7	1	75	77	62	6.8	6.8	1.7	1.7
	2	77	78	67	3.4	3.6	1.8	1.2
	3	81	82	70	2.5	2.8	4.7	3.6
	4	84	86	72	2.4	2.6	5.6	4.6
E_8	1	70	77	62	8.1	8.2	2.6	2.1
	2	78	81	67	4.0	4.3	1.6	1.2
	3	82	83	70	2.7	3.1	3.9	3.2
	4	84	86	72	2.5	2.7	4.9	4.0
E_9	1	78	79	62	10.0	9.0	3.3	2.5
	2	79	81	66	6.1	5.5	2.5	1.4
	3	82	84	69	3.4	3.5	3.6	3.6
	4	86	85	71	3.0	3.3	4.0	3.9
E_{10}	1	79	81	62	11.0	7.7	2.0	1.5
	2	80	82	66	6.4	5.7	2.7	1.1
	3	83	84	69	3.4	3.4	3.4	3.2
	4	86	88	72	3.2	4.5	5.1	4.3

EAST RIVER

1957 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_1	1	75	78	70	2.3	2.2	2.9	1.8
	2	77	80	71	2.6	3.7	2.2	1.2
	3	80	80	74	1.4	1.6	2.2	1.7
	4	78	80	66	1.6	2.2	2.4	1.6
E_2	1	74	76	70	2.1	2.5	2.8	1.6
	2	78	80	71	1.8	2.3	2.9	2.0
	3	80	81	74	1.1	1.6	3.0	2.1
	4	79	80	66	1.5	.0	2.8	1.3
E_3	1	75	75	70	2.0	2.2	4.8	2.0
	2	79	81	72	1.5	2.4	4.0	2.1
	3	82	81	74	0.7	1.3	4.4	2.5
	4	78	80	67	1.9	2.0	5.8	2.2
E_4	1	78	80	68	2.5	2.6	2.8	2.4
	2	79	81	72	1.1	1.3	3.2	1.8
	3	79	81	73	1.7	2.1	2.4	1.3
	4	80	81	68	1.5	1.8	3.6	0.9
E_5	1	80	80	67	2.8	2.8	2.0	1.4
	2	82	84	71	1.4	2.2	2.2	1.4
	3	82	83	72	2.2	2.2	1.6	1.5
	4	81	83	68	2.3	2.9	2.5	1.4

EAST RIVER

1957 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_6	1	80	82	66	2.8	4.0	2.0	1.2
	2	82	84	72	2.0	2.3	2.2	0.8
	3	81	84	72	2.3	2.7	2.1	1.6
	4	83	83	68	1.8	2.2	3.5	2.2
E_7	1	82	82	65	4.1	4.2	1.6	0.8
	2	84	86	70	2.8	3.5	2.0	1.0
	3	85	87	72	3.2	3.5	2.0	0.8
	4	85	87	68	1.9	2.8	2.3	1.2
E_8	1	82	83	65	5.4	4.8	2.0	0.8
	2	86	84	71	4.1	4.2	2.2	1.2
	3	86	87	72	3.7	4.1	1.6	1.2
	4	86	87	68	3.5	4.0	1.2	0.3
E_9	1	82	83	65	6.2	6.0	2.7	1.0
	2	86	84	71	5.1	4.4	2.0	1.0
	3	86	87	71	3.1	4.6	1.7	1.0
	4	85	87	68	3.8	3.9	1.0	1.1
E_{10}	1	82	82	64	6.6	6.6	1.6	0.8
	2	86	84	71	6.1	4.9	3.4	1.1
	3	87	86	72	5.1	4.5	1.7	0.7
	4	85	85	67	4.3	5.1	1.3	0.5

EAST RIVER

1958 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_1	1	68	72	63	4.2	4.2	1.5	1.4
	2	75	77	70	3.0	3.2	1.8	2.0
	3	73	75	73	1.8	2.4	2.6	1.8
	4	74	76	69	2.4	2.7	2.3	1.2
E_2	1	70	72	63	3.5	3.4	1.8	1.6
	2	73	75	70	2.3	2.8	2.4	1.1
	3	75	76	73	1.9	2.2	3.0	1.7
	4	74	76	70	1.9	2.3	2.2	1.4
E_3	1	71	72	64	4.5	5.2	2.2	2.0
	2	73	74	71	2.4	2.8	4.0	2.1
	3	76	77	72	1.6	1.8	3.6	2.4
	4	75	76	70	1.5	2.2	3.6	2.2
E_4	1	69	70	62	4.1	4.1	2.4	1.7
	2	76	78	68	3.1	3.3	1.7	1.0
	3	75	77	73	2.3	2.7	2.5	1.3
	4	75	77	70	1.9	2.6	2.5	1.6
E_5	1	68	72	61	4.0	4.6	1.9	0.8
	2	78	78	68	2.8	3.3	2.2	1.4
	3	75	77	72	1.8	2.1	2.0	1.6
	4	76	77	69	2.3	3.2	2.5	1.0

EAST RIVER

1958 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_6	1	70	75	61	4.6	4.9	2.0	1.4
	2	76	78	68	3.1	3.8	2.0	1.1
	3	76	79	71	2.4	2.9	1.5	0.7
	4	76	78	68	3.0	3.8	1.9	0.5
E_7	1	73	75	61	5.1	6.4	1.0	1.1
	2	76	77	68	4.0	4.5	1.7	0.9
	3	77	81	70	2.8	3.1	1.1	0.7
	4	78	80	68	3.4	4.2	1.8	0.6
E_8	1	76	77	60	5.8	6.2	1.8	1.1
	2	78	78	66	4.8	5.0	1.1	0.8
	3	81	82	69	2.9	3.4	1.4	0.6
	4	82	83	68	4.0	4.2	1.1	0.3
E_9	1	75	78	60	7.0	6.9	1.7	1.3
	2	79	80	68	4.9	5.2	1.7	1.2
	3	81	82	70	3.7	4.0	1.2	0.5
	4	79	83	68	4.2	4.8	1.4	0.7
E_{10}	1	76	78	60	7.5	7.5	1.5	1.1
	2	79	80	67	6.0	6.7	2.0	1.3
	3	82	82	70	3.4	3.7	1.3	0.2
	4	81	83	68	4.7	5.0	1.2	0.2

EAST RIVER

1959 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_1	1	71	73	68	2.8	3.5	2.0	1.7
	2	75	78	71	2.5	2.6	1.5	0.9
	3	80	81	76	1.1	1.3	1.7	1.6
	4	80	81	69	2.4	2.8	1.8	1.1
E_2	1	72	73	67	2.4	2.3	3.1	2.1
	2	75	75	71	1.8	1.2	2.5	3.2
	3	78	80	75	0.9	1.2	2.2	1.4
	4	79	80	69	1.9	2.2	2.8	1.7
E_3	1	74	73	68	2.3	2.7	4.2	2.7
	2	75	75	72	1.5	2.2	2.5	2.3
	3	79	79	75	1.3	1.4	3.3	2.4
	4	80	81	70	2.1	2.2	3.0	2.0
E_4	1	73	74	67	2.0	2.7	2.2	2.5
	2	77	76	72	1.0	1.9	1.8	1.8
	3	79	81	76	1.1	1.3	2.2	2.2
	4	81	82	72	2.2	2.6	2.0	2.0
E_5	1	74	74	66	2.0	4.6	1.6	1.5
	2	77	78	71	1.2	2.0	1.2	1.5
	3	82	83	76	1.6	1.9	1.5	1.2
	4	82	85	71	2.5	2.7	2.0	1.4

EAST RIVER

1959 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_6	1	78	80	65	3.4	3.4	1.7	1.3
	2	78	80	70	1.4	2.5	1.4	1.0
	3	82	85	76	1.7	2.4	1.8	1.4
	4	84	84	71	2.3	3.1	1.8	1.3
E_7	1	80	78	65	3.7	4.4	0.1	0.6
	2	78	80	69	2.0	2.9	1.1	1.2
	3	84	85	75	2.4	2.8	1.4	0.9
	4	85	84	72	3.3	3.6	1.6	0.6
E_8	1	82	81	64	5.4	5.7	1.6	1.2
	2	80	80	68	3.3	3.8	1.9	1.3
	3	86	88	75	2.9	3.2	1.2	1.5
	4	86	86	71	4.6	4.9	1.0	0.8
E_9	1	82	81	64	6.5	6.4	1.0	0.7
	2	81	82	68	5.1	4.5	2.3	1.4
	3	87	87	74	4.0	3.8	1.8	1.5
	4	87	87	71	4.5	5.1	1.2	0.9
E_{10}	1	80	81	64	5.7	6.1	1.7	1.2
	2	81	83	67	4.6	4.2	2.0	1.0
	3	88	88	74	4.2	3.9	1.5	1.0
	4	86	87	70	5.2	5.5	1.0	0.9

1959 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		72.5	66.7	3.33	40.8	2.02
July	E	73.0	70.8	2.38	30.5	1.43
August	1	78.5	73.6	1.36	17.8	1.62
Sept.		82.5	72.4	2.19	29.0	1.49
June		72.6	66.5	2.55	30.8	2.82
July	E	71.8	70.5	2.45	31.3	2.23
August	2	78.8	72.7	1.10	14.3	1.65
Sept.		79.1	73.0	1.79	24.4	2.51
June		73.7	76.5	2.62	32.2	3.58
July	E	72.5	71.3	1.90	24.3	2.60
August	3	79.0	73.0	1.25	16.5	2.73
Sept.		79.8	73.0	2.10	2.69	2.76
June		74.0	67.0	2.40	29.0	2.40
July	E	76.4	71.6	1.49	19.3	1.80
August	4	78.5	76.5	.85	10.5	1.63
Sept.		81.6	73.9	2.01	28.6	1.96
June		74.0	66.0	3.30	41.0	1.60
July	E	77.4	70.8	1.63	20.6	1.39
August	5	81.5	75.8	1.43	19.5	1.28
Sept.		83.8	73.4	2.36	31.5	1.66

1959 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E 6	79.0	65.0	3.40	42.0	1.50
July		78.8	70.0	2.00	25.5	1.21
August		82.3	75.5	1.70	23.3	1.33
Sept.		84.0	73.5	2.60	34.0	1.71
June	E 7	79.0	65.0	4.10	49.0	0.40
July		78.5	69.1	2.50	31.4	1.15
August		84.0	75.5	2.30	31.3	1.20
Sept.		85.3	83.0	3.20	42.8	1.56
June	E 8	82.0	64.0	5.60	68.0	1.40
July		79.6	68.4	3.55	45.0	1.59
August		80.5	75.3	2.85	39.3	1.10
Sept.		86.6	72.5	4.00	53.3	1.30
June	E 9	82.0	64.0	6.50	78.0	0.90
July		81.7	67.8	4.80	60.5	1.84
August		86.5	74.0	3.70	50.0	1.45
Sept.		87.6	72.5	4.50	59.9	2.30
June	E 10	81.0	64.0	5.90	72.0	1.50
July		82.3	67.4	4.45	55.3	1.53
August		87.3	73.8	4.00	54.5	1.25
Sept.		88.0	72.2	4.73	63.6	1.10

EAST RIVER

1960 SUMMARY SHEET

Station	Period	% Seawater top	% Seawater bottom	Temperature top & bottom	Dissolved O_2 top	Dissolved O_2 bottom	BOD 5-day ppm top	BOD 5-day ppm bottom
E_1	1	71	68	65	3.0	3.3	1.9	1.7
	2	70	74	68	2.9	3.1	2.3	2.2
	3	77	76	72	1.9	2.3	1.7	1.3
	4	72	71	74	1.5	1.7	2.0	1.3
E_2	1	71	68	64	2.7	2.9	2.1	1.9
	2	70	71	74	1.2	1.7	1.7	1.8
	3	79	76	71	2.0	2.6	2.4	2.0
	4	71	71	74	1.2	1.7	1.7	1.8
E_3	1	71	75	65	3.0	3.5	2.3	2.2
	2	70	70	68	2.0	3.5	3.4	3.0
	3	77	76	72	1.6	1.9	3.5	3.5
	4	73	72	74	1.2	1.7	2.7	2.1
E_4	1	73	75	67	2.9	2.6	2.9	1.8
	2	72	72	70	2.0	2.2	2.6	2.5
	3	77	76	72	1.9	2.0	2.2	1.5
	4	72	73	75	1.8	2.3	2.8	1.1
E_5	1	74	75	66	2.9	3.5	1.8	1.8
	2	73	75	69	2.1	2.1	2.2	1.4
	3	80	81	71	1.8	2.4	1.2	1.0
	4	74	77	74	1.9	2.2	3.3	1.7

EAST RIVER

1960 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_6	1	76	76	66	3.5	3.6	2.1	1.5
	2	77	78	69	2.8	3.3	1.9	1.8
	3	81	81	72	2.2	2.6	1.7	0.7
	4	75	75	75	2.0	2.4	2.7	3.4
E_7	1	79	80	65	4.7	4.9	1.5	1.5
	2	78	79	68	3.8	4.2	2.0	1.1
	3	81	80	81	3.2	3.3	1.3	1.9
	4	79	79	74	3.0	3.1	3.3	1.7
E_8	1	79	80	65	5.8	5.6	1.7	1.6
	2	82	82	67	5.5	5.7	1.9	1.7
	3	84	85	70	4.5	3.9	1.2	0.8
	4	81	82	73	3.6	3.7	3.2	2.4
E_9	1	79	81	65	6.8	6.2	1.9	1.7
	2	82	83	66	6.8	6.2	1.8	2.2
	3	86	84	70	5.7	4.6	2.9	1.2
	4	81	82	73	4.4	4.5	2.7	2.6
E_{10}	1	80	81	63	6.9	6.5	1.8	1.1
	2	82	82	66	7.6	6.2	3.0	0.9
	3	86	86	70	5.8	4.3	4.4	0.7
	4	82	85	73	4.6	4.6	1.4	0.8

1960 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_1	70.0	66.0	3.10	38.4	1.50
July		76.5	69.2	2.42	30.6	2.23
August		71.6	74.2	1.62	22.0	1.39
Sept.		--	--	--	--	--
June	E_2	69.0	66.0	2.50	29.7	1.90
July		73.8	70.2	2.43	31.1	2.65
August		72.5	74.2	1.41	18.7	1.56
Sept.		--	--	--	--	--
June	E_3	71.0	67.0	2.60	32.1	2.30
July		75.2	70.5	1.63	23.4	2.85
August		72.2	74.3	1.42	18.8	2.34
Sept.		--	--	--	--	--
June	E_4	72.0	68.0	2.40	29.4	1.80
July		75.5	71.7	1.93	25.4	2.16
August		73.2	74.5	2.09	27.8	1.95
Sept.		--	--	--	--	--
June	E_5	74.0	68.0	2.60	32.1	1.20
July		78.8	70.6	2.03	29.2	1.43
August		76.4	73.8	2.16	28.7	2.23
Sept.		--	--	--	--	--

1960 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		76.0	67.0	3.20	40.0	1.93
July	E	80.5	71.0	2.76	36.0	1.52
August	6	76.1	74.1	2.18	30.1	2.68
Sept.		--	--	--	--	--
June		78.5	66.0	5.24	53.1	1.57
July	E	80.3	70.8	3.73	48.5	1.50
August	7	79.5	73.4	2.97	39.6	1.89
Sept.		--	--	--	--	--
June		80.6	65.3	5.95	69.3	1.67
July	E	83.8	70.2	4.92	63.7	1.58
August	8	81.8	72.4	3.69	48.9	2.37
Sept.		--	--	--	--	--
June		80.5	65.0	6.68	80.4	1.62
July	E	85.8	69.0	5.46	70.5	2.23
August	9	81.3	72.3	4.62	60.9	2.52
Sept.		--	--	--	--	--
June		81.1	64.0	7.10	82.1	1.23
July	E	86.0	69.3	6.53	78.2	2.20
August	10	83.3	72.2	4.46	59.2	1.69
Sept.		--	--	--	--	--

EAST RIVER

1961 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_1	1	67	69	64	3.2	2.9	2.3	2.2
	2	70	69	67	3.4	3.4	2.0	2.3
	3	73	76	74	1.9	2.1	1.2	1.8
	4	73	72	77	1.3	1.1	0.0	0.7
E_2	1	68	68	64	3.2	2.8	2.9	3.2
	2	68	70	68	3.2	3.3	2.2	2.4
	3	75	73	75	1.6	1.4	2.0	0.9
	4	69	64	77	1.1	2.1	0.2	5.4
E_3	1	70	77	64	4.0	3.2	3.8	3.1
	2	68	67	69	3.4	3.5	3.4	2.4
	3	74	73	75	1.3	1.2	2.7	1.8
	4	69	72	76	1.0	0.6	1.3	1.7
E_4	1	69	70	65	3.8	3.4	3.0	2.7
	2	70	71	69	2.6	2.6	2.0	2.2
	3	75	76	74	1.7	1.7	2.1	1.6
	4	78	67	77	1.3	1.5	1.4	0.6
E_5	1	74	74	64	4.0	3.8	3.1	2.2
	2	74	72	68	2.7	2.6	2.2	1.7
	3	77	73	74	2.0	1.5	1.6	1.9
	4	77	77	77	1.4	2.3	1.4	1.3

EAST RIVER

1961 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
E_6	1	76	75	64	4.8	4.5	2.5	2.1
	2	73	74	69	3.9	4.3	3.6	2.1
	3	77	77	73	2.0	1.8	1.4	1.8
	4	81	78	77	2.2	2.0	0.8	1.6
E_7	1	78	80	64	6.2	6.5	2.9	2.2
	2	76	76	67	4.8	5.4	4.3	2.8
	3	78	81	72	2.9	2.8	1.2	1.0
	4	86	87	76	2.8	2.8	1.5	2.4
E_8	1	82	80	61	7.0	6.8	2.8	1.8
	2	80	82	67	7.4	6.7	5.8	3.8
	3	80	81	72	3.7	3.5	0.8	1.1
	4	84	87	76	4.0	4.0	- -	- -
E_9	1	82	82	61	8.0	7.6	2.4	1.5
	2	80	82	68	7.2	6.4	6.7	3.3
	3	82	82	72	5.8	3.8	2.5	1.6
	4	86	86	77	5.8	4.3	1.7	1.6
E_{10}	1	78	81	60	8.6	8.0	2.4	2.2
	2	80	80	68	7.0	6.5	5.7	4.2
	3	84	83	71	6.0	4.1	2.8	0.9
	4	86	86	74	5.5	3.4	1.0	0.7

1961 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E 1	68.2	63.8	2.90	35.8	2.00
July		69.6	69.0	3.13	40.5	1.70
August		78.6	74.7	1.85	24.7	1.00
Sept.		--	--	--	--	--
June	E 2	64.7	66.8	3.02	35.5	3.10
July		70.0	68.6	2.73	33.1	1.65
August		76.2	75.5	1.62	21.8	1.85
Sept.		--	--	--	--	--
June	E 3	71.8	64.5	3.60	42.7	3.90
July		70.5	69.5	2.83	35.3	2.93
August		75.4	75.7	1.30	17.7	1.23
Sept.		--	--	--	--	--
June	E 4	69.5	65.0	3.62	43.3	2.85
July		70.8	71.5	2.09	26.6	1.98
August		72.4	74.1	1.69	40.5	1.59
Sept.		81.5	79.0	4.25	19.5	0.65
June	E 5	74.3	64.0	3.93	46.5	2.82
July		73.3	71.4	2.43	29.6	2.65
August		76.6	73.9	1.83	24.1	1.47
Sept.		75.0	78.0	1.65	23.0	1.80

1961 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E 6	75.3	64.0	4.65	55.8	2.33
July		74.4	71.4	2.86	36.8	2 24
August		77.9	75.0	2.03	26.9	1.39
Sept.		8.75	78.0	2.40	35.5	.80
June	E 7	79.3	63.5	6.32	76.2	2.53
July		76.4	69.6	3.94	50.0	2.44
August		82.0	72.9	3.01	40.8	1.16
Sept.		89.0	76.5	2.75	38.5	1.80
June	E 8	80.7	61.2	6.88	80.3	2.27
July		80.1	69.5	5.29	82.9	2.36
August		83.3	72.5	3.85	46.9	.50
Sept.		86.5	78.0	5.00	71.0	.80
June	E 9	82.2	60.7	7.80	92.5	2.24
July		81.3	69.5	5.90	76.4	1.93
August		83.3	73.0	4.69	62.8	1.39
Sept.		88.0	76.5	5.60	78.5	.90
June	E 10	79.7	60.2	8.28	97.2	2.28
July		81.4	70.3	6 01	76.5	1.87
August		83.3	72.0	4.70	62.3	1.06
Sept.		88.5	75.5	4.85	67.5	.80

1962 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_1	73.8	67.3	1.89	33.4	1.77
July		83.0	71.8	1.62	21.2	2.15
August		83.6	74.4	1.54	20.9	1.85
Sept.		86.0	72.0	1.55	20.7	
June	E_2	75.6	66.9	1.93	30.9	1.85
July		80.3	71.7	1.57	21.0	2.07
August		83.6	73.7	1.45	21.0	1.60
Sept.		83.0	73.0	0.50	6.6	
June	E_3	76.8	66.5	1.80	22.8	2.40
July		81.0	72.0	1.35	17.6	3.25
August		82.6	74.3	1.29	17.1	1.25
Sept		83.0	73.0	1.50	20.1	
June	E_4	76.1	67.8	2.53	31.2	3.21
July		76.0	73.0	1.84	24.1	1.87
August		82.7	75.0	1.15	15.8	1.74
Sept.						
June	E_5	79.8	67.4	2.66	33.3	3.09
July		83.8	72.5	2.05	27.3	1.53
August		78.3	74.5	1.62	22.2	1.53
Sept.						

1962 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_6	76.4	67.5	2.94	36.5	3.54
July		82.5	71.6	2.31	31.1	2.26
August		86.7	74.5	1.75	23.9	1.09
Sept.						
June	E_7	74.4	66.3	4.40	54.8	3.26
July		86.4	70.1	3.21	42.9	1.56
August		88.3	74.7	2.65	36.4	.78
Sept.						
June	E_8	84.5	64.8	5.75	70.2	3.09
July		86.0	70.0	4.10	53.5	1.74
August		92.2	73.8	3.15	43.2	1.34
Sept.						
June	E_9	86.6	64.6	6.79	84.1	3.10
July		86.5	69.1	5.24	64.4	2.04
August		[illegible]2	74.0	3.75	51.4	1.55
Sept.						
June	E_{10}	83.5	64.3	6.75	82.5	2.64
July		86.3	69.9	5.55	72.1	2.01
August		93.5	74.0	4.22		1.82
Sept.						

1963 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		75.0	68.0	2.48	31.7	2.25
July	E_1	80.9	72.5	2.09	24.9	1.69
August		82.9	72.7	1.71	22.9	1.89
Sept.		81.0	71.0	1.50	18.9	2.15
June		81.5	67.8	1.73	22.6	3.13
July	E_2	81.3	72.3	1.90	23.3	1.80
August		81.9	72.3	1.44	19.1	1.86
Sept.		82.5	70.5	1.55	20.3	2.40
June		82.3	68.3	1.63	21.1	2.85
July	E_3	82.1	72.8	1.50	19.9	2.63
August		83.9	72.9	1.25	16.3	2.46
Sept.		85.0	71.0	1.75	23.2	1.90
June		76.0	67.7	2.02	25.0	2.57
July	E_4	82.0	70.8	2.43	31.5	2.17
August		82.8	74.0	1.74	23.3	2.03
Sept.		83.8	72.0	1.90	23.9	2.35
June		76.2	66.5	2.22	27.4	2.00
July	E_5	83.3	69.3	2.73	35.4	2.05
August		83.8	76.4	2.09	27.9	1.81
Sept.		83.8	72.3	1.95	23.2	2.85

1963 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_6	78.7	66.5	1.77	24.0	2.02
July		78.0	73.0	2.80	35.7	2.38
August		83.8	72.3	2.44	32.6	1.85
Sept.		82.8	71.5	2.35	26.1	
June	E_7	77.5	66.8	4.05	48.5	2.15
July		84.3	67.3	4.43	55.7	2.10
August		83.1	71.9	3.35	45.1	1.60
Sept.		84.8	71.8	3.33	40.9	1.75
June	E_8	76.3	64.5	5.37	66.0	2.32
July		86.0	66.0	5.73	73.9	2.07
August		87.9	71.1	3.85	50.8	1.69
Sept.		85.0	71.0	4.53	59.5	1.48
June	E_9	82.8	66.3	7.20	89.3	2.93
July		88.5	67.5	6.28	80.7	2.45
August		87.6	71.3	4.95	65.5	1.49
Sept.		89.0	71.0	5.15	68.0	1.05
June	E_{10}	84.5	65.5	7.15	89.2	2.33
July		87.8	68.3	8.18	106.5	2.88
August		88.3	70.4	5.06	66.2	1.65
Sept.		88.3	71.5	4.98	69.5	1.33

1964 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_1	79.8	63.0	3.67	44.6	2.22
July		75.7	71.3	1.83	23.6	3.28
August		78.6	71.5	2.63	34.3	4.33
Sept.		76.5	72.0	4.55	64.1	----
June	E_2	75.0	63.3	3.05	36.4	2.80
July		76.5	70.5	1.74	26.5	2.83
August		76.4	72.0	2.20	28.7	4.53
Sept.		75.0	72.0	3.05	39.8	----
June	E_3	77.5	63.7	2.92	37.2	3.38
July		76.5	70.4	2.24	36.6	4.10
August		77.8	72.5	2.03	26.5	4.00
Sept.		76.5	72.0	6.10	79.6	----
June	E_4	75.6	64.3	2.65	31.9	3.30
July		76.8	70.3	1.93	24.6	5.58
August		75.1	72.6	2.64	34.7	3.60
Sept.		78.0	77.3	1.93	25.8	2.45
June	E_5	77.3	63.5	3.61	43.4	3.04
July		77.5	73.5	1.30	17.3	6.90
August		81.0	71.6	2.90	38.1	5.08
Sept.		82.3	73.8	2.85	38.4	1.73

1964 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_6	72.0	63.6	4.21	49.7	2.82
July		79.5	73.0	1.80	23.9	5.45
August		81.9	71.6	3.23	42.4	4.25
Sept.		79.5	73.5	2.85	38.1	2.40
June	E_7	79.5	62.8	5.29	63.4	2.90
July		79.5	72.0	2.55	33.5	6.30
August		84.1	70.8	4.16	19.8	4.25
Sept.		82.0	74.0	2.13	28.7	2.40
June	E_8	80.5	62.0	6.60	78.7	3.14
July		81.5	71.0	4.15	54.1	6.25
August		35.6	70.1	4.66	61.5	3.73
Sept.		88.3	72.5	3.93	52.8	1.73
June	E_9	80.8	62.1	7.94	96.0	4.58
July		83.0	72.0	5.70	75.4	5.35
August		84.9	70.3	4.95	63.5	2.77
Sept.		82.5	72.5	3.75	49.8	----
June	E_{10}	81.6	61.5	8.16	106.7	3.86
July		83.0	70.0	6.40	83.0	5.85
August		87.5	69.9	5.31	69.5	3.05
Sept.		88.0	71.8	4.33	57.5	1.80

1965 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_1	74.6	6.40	2.43	28.81	1.85
July		79.4	71.0	1.73	22.66	2.27
August		81.1	73.2	1.63	21.87	1.37
June	E_2	77.5	64.6	1.86	24.60	2.55
July		79.7	70.5	1.55	20.40	1.75
August		82.6	73.3	1.30	17.28	2.28
June	E_3	77.1	65.6	1.86	22.73	3.36
July		80.2	70.9	1.50	20.52	1.85
August		81.8	73.8	1.70	22.82	2.00
June	E_4	77.8	66.1	2.85	34.81	2.18
July		82.5	71.1	1.41	18.56	1.36
August		81.5	73.1	1.29	17.17	1.49
June	E_5	81.6	65.0	3.61	51.06	2.40
July		83.1	68.8	2.45	33.36	1.30
August		83.1	71.9	2.36	31.18	1.27
June	E_6	82.1	65.6	3.05	50.05	1.77
July		83.8	69.1	2.41	30.58	1.46
August		84.0	72.0	2.12	24.58	1.30

1965 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_7	83.0	64.7	4.01	46.61	2.04
July		82.0	68.1	2.78	35.30	1.06
August		83.6	71.5	2.53	33.43	1.13
June	E_8	82.6	63.5	5.11	61.91	1.45
July		82.5	67.8	4.50	57.13	1.71
August		85.0	70.7	3.51	45.92	1.22
June	E_9	83.0	63.0	5.90	70.6	1.55
July		85.0	67.0	4.90	61.5	2.28
August		84.0	70.0	4.80	63.0	1.62
June	E_{10}	83.0	63.0	6.30	76.4	1.88
July		85.0	67.0	5.30	66.5	2.44
August		84.0	70.0	5.20	70.0	1.63

1965 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_1	74.6	64.0	2.43	28.81	1.85
July		79.4	71.0	1.73	22.66	2.27
August		81.1	73.2	1.63	21.87	1.37
June	E_2	77.5	64.6	1.86	24.60	2.55
July		79.7	70.5	1.55	20.40	1.75
August		82.6	73.3	1.30	17.28	2.28
June	E_3	77.1	65.6	1.86	22.73	3.36
July		80.2	70.9	1.50	20.52	1.85
August		81.8	73.8	1.70	22.82	2.00
June	E_4	77.8	66.1	2.85	34.81	2.18
July		82.5	71.1	1.41	18.56	1.36
August		81.5	73.1	1.29	17.17	1.49
June	E_5	81.6	65.0	3.61	51.06	2.40
July		83.1	68.8	2.45	33.36	1.30
August		83.1	71.9	2.36	31.18	1.27
June	E_6	82.1	65.6	3.05	50.05	1.77
July		83.8	69.1	2.41	30.58	1.46
August		84.0	72.0	2.12	24.58	1.30

1965 SUMMARY

EAST RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	E_7	83.0	64.7	4.01	46.61	2.04
July		82.0	68.1	2.78	35.30	1.06
August		83.6	71.5	2.53	33.43	1.13
June	E_8	82.6	64.5	5.11	61.91	1.45
July		82.5	67.8	4.50	57.13	1.71
August		85.0	70.7	3.51	45.92	1.22
June	E_9	83.0	63.0	5.90	70.60	1.55
July		85.0	67.0	4.90	61.50	2.28
August		84.0	70.0	4.80	63.00	1.62
June	E_{10}	83.0	63.0	6.30	76.40	1.88
July		85.0	67.0	5.30	66.50	2.44
August		84.0	70.0	5.20	70.00	1.63

1959 SUMMARY

JAMAICA BAY

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	J 1	85.8	65.3	7.88	97.5	2.33
July		88.3	70.0	6.60	86.7	1.52
August		91.3	73.7	5.20	71.5	1.03
Sept.		92.3	66.7	5.92	75.3	1.33
June	J 2	83.3	67.8	8.13	10.3	3.23
July		87.0	73.3	5.23	70.7	2.05
August		86.8	73.2	4.88	66.0	1.30
Sept.		91.0	67.0	6.03	77.2	1.48
June	J 3	85.3	69.8	6.90	90.0	2.50
July		86.2	73.8	4.70	63.8	1.01
August		86.8	74.7	3.98	54.6	1.03
Sept.		89.1	66.8	5.40	68.8	1.40
June	J 5	83.3	69.5	7.53	97.3	3.00
July		86.5	72.5	5.58	74.8	1.98
August		86.8	75.8	4.50	63.2	1.25
Sept.		89.1	67.8	5.78	74.1	1.95
June	J 7	81.8	71.0	5.60	73.5	2.58
July		82.0	74.5	4.45	72.5	3.03
August		83.5	76.2	3.38	47.2	2.37
Sept.		85.1	68.7	4.05	52.0	1.47

JAMAICA BAY

1960 SUMMARY SHEET

Station	Period	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top	bottom
J - 1	1	5.8	6.3	1.5	0.7
	2	7.2	7.2	1.9	1.3
	3	6.2	6.2	1.9	0.5
	4	6.4	6.3	2.8	1.0
J - 5	1	5.5	5.7	1.6	0.6
	2	5.5	6.4	2.1	1.8
	3	5.8	5.7	2.1	1.5
	4	5.0	5.8	2.8	1.6
J - 7	1	5.0	4.6	3.2	1.5
	2	5.0	4.6	3.4	2.4
	3	4.5	3.5	2.8	1.4
	4	5.4	4.4	4.2	1.2
J - 2	1	4.7	5.0	2.8	0.9
	2	5.8	6.2	2.8	1.4
	3	5.4	5.3	2.6	1.2
	4	6.1	6.0	2.2	1.8
J - 3	1	3.9	4.1	1.5	0.5
	2	4.8	5.2	2.3	1.0
	3	4.3	4.8	2.4	0.9
	4	4.9	5.3	1.8	1.4

1960 SUMMARY

JAMAICA BAY

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		88.0	67.5	6.78	85.8	1.15
July	J	92.6	71.8	7.00	94.4	1.95
August	1	88.9	72.4	6.20	83.3	1.45
Sept.		90.3	73.0	6.33	86.1	1.93
June		87.8	71.0	5.87	76.0	1.78
July	J	86.3	73.7	5.77	78.2	2.28
August	2	86.0	73.5	5.40	73.0	1.86
Sept.		84.5	75.0	6.05	83.5	1.83
June		85.2	72.5	4.43	59.7	1.03
July	J	83.0	75.5	5.23	70.6	2.08
August	3	84.6	74.5	4.58	4.58	1.76
Sept.		84.5	75.8	5.10	70.1	1.75
June		86.2	70.6	5.88	76.8	1.31
July	J	85.6	75.0	6.56	9.02	2.25
August	5	82.8	74.1	5.61	7.59	1.78
Sept.		82.3	75.0	5.18	7.06	2.25
June		86.1	72.4	4.70	62.6	2.83
July	J	84.0	75.2	4.90	66.8	1.98
August	7	78.3	74.5	4.13	55.7	2.01
Sept.		79.8	76.3	4.90	67.8	2.05

JAMAICA BAY

1961 SUMMARY SHEET

Station	Period	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top	bottom
J - 1	1	7.7	7.1	3.9	2.8
	2	7.0	6.8	2.1	1.3
	3	5.8	5.7	1.2	0.5
	4	5.2	5.1	1.5	0.7
J - 5	1	6.8	6.2	3.2	2.8
	2	6.9	6.8	2.4	2.3
	3	5.0	5.2	2.0	1.4
	4	4.2	4.3	1.2	1.0
J - 7	1	4.4	4.2	4.2	2.4
	2	5.5	4.8	5.6	1.7
	3	4.2	3.0	5.2	1.9
	4	6.1	3.8	2.9	1.5
J - 2	1	6.9	6.9	4.8	2.5
	2	6.7	6.5	2.6	2.0
	3	5.1	4.6	2.0	1.4
	4	5.8	5.0	1.9	1.0
J - 3	1	6.3	6.3	4.1	2.7
	2	6.0	5.9	2.6	2.6
	3	4.4	4.2	1.3	1.4
	4	4.1	4.7	1.8	0.8

1961 SUMMARY

JAMAICA BAY

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	J 1	86.1	63.5	7.30	88.8	1.90
July		89.3	72.8	6.48	87.0	.80
August		88.8	73.1	5.43	73.3	1.10
Sept.		90.0	74.8	5.58	76.8	.60
June	J 2	80.4	65.8	6.53	80.6	2.33
July		82.7	74.3	6.10	83.3	1.00
August		79.8	75.6	5.29	69.0	1.63
Sept.		86.0	77.0	5.55	77.8	1.80
June	J 3	82.1	65.9	5.89	73.3	2.43
July		82.2	74.8	5.62	75.8	1.40
August		80.3	75.6	4.16	67.0	1.17
Sept.		82.5	77.8	4.95	65.8	1.40
June	J 5	79.8	66.3	6.04	74.8	2.60
July		77.7	75.3	6.78	91.8	1.15
August		81.8	75.8	4.51	62.3	1.22
Sept.		82.0	77.8	4.80	67.5	.85
June	J 7	74.1	67.6	4.30	53.4	3.40
July		78.0	76.2	4.60	60.7	2.15
August		76.0	76.5	3.49	48.1	3.28
Sept.		78.3	79.3	5.73	81.0	3.00

1962 SUMMARY

JAMAICA BAY

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	J1	89.8	64.7	6.50	81.3	1.72
July		90.1	72.0	6.16	79.2	1.43
August		95.0	71.0	6.61	88.7	1.45
Sept.		87.0	67.0	4.75	60.2	1.30
June	J2	85.2	74.3	5.73	72.1	2.74
July		87.6	74.3	5.70	77.8	2.30
August		91.0	73.3	5.98	81.5	1.78
Sept.		85.0	68.0	4.90	62.5	1.10
June	J3	86.3	68.0	5.02	64.9	2.06
July		86.6	75.3	4.90	67.2	3.05
August		90.0	73.9	5.20	71.3	2.50
Sept.		86.0	70.0	4.30	56.2	1.05
June	J5	86.3	68.2	5.87	76.1	2.52
July		87.6	74.4	4.54	62.2	2.15
August		88.8	74.0	5.24	73.0	1.18
Sept.		83.0	67.0	4.15	52.2	1.15
June	J7	84.2	70.7	3.67	48.4	2.08
July		83.6	75.6	4.01	55.0	2.66
August		87.5	74.8	4.59	62.5	2.25
Sept.		84.0	69.5	2.45	31.7	1.95

1963 SUMMARY

JAMAICA BAY

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	J_1	92.0	64.5	7.08	88.5	2.00
July		92.0	71.9	6.20	86.4	1.99
August		93.8	68.8	6.22	81.6	2.09
Sept.		91.3	67.3	6.95	89.4	1.58
June	J_2	90.8	70.0	6.73	88.9	3.15
July		91.3	74.3	5.73	78.6	3.19
August		93.2	71.0	6.70	89.8	3.33
Sept.		92.0	68.8	6.88	89.3	2.58
June	J_3	92.5	70.5	6.78	91.9	2.98
July		90.5	74.4	4.79	66.8	3.44
August		94.2	72.7	6.28	77.9	3.13
Sept.		89.5	68.0	6.28	81.4	2.85
June	J_5	89.8	70.8	7.50	101.0	2.53
July		89.5	74.1	5.53	76.3	2.39
August		92.3	72.2	6.68	90.6	2.82
Sept.		89.5	69.0	6.38	82.9	2.00
June	J_7	81.8	72.3	3.10	42.3	2.27
July		86.9	75.4	2.33	33.1	4.53
August		87.8	73.8	6.13	74.8	4.03
Sept.		89.3	69.5	4.73	61.4	3.75

1964 SUMMARY

JAMAICA BAY

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	J_1	91.0	64.0	6.83	32.4	3.37
July		90.0	70.9	6.13	81.9	3.38
August		91.9	69.8	6.85	89.8	3.00
Sept.		87.0	72.0	6.60	87.9	3.60
June	J_2	87.7	65.3	6.82	85.1	3.15
July		86.5	72.6	5.31	71.3	3.98
August		87.8	70.9	6.24	82.4	3.56
Sept.		87.5	72.5	6.60	88.7	4.40
June	J_3	85.0	65.8	4.78	60.0	3.58
July		85.0	72.8	7.28	58.7	3.95
August		86.1	71.5	5.29	70.1	3.59
Sept.		88.0	74.0	----	54.7	4.35
June	J_5	87.5	66.2	6.23	77.4	2.92
July		86.6	73.0	5.16	61.9	3.20
August		89.1	71.4	5.54	73.6	3.04
Sept.		87.5	73.5	6.40	86.9	3.90
June	J_7	81.7	66.5	4.73	43.8	2.96
July		81.0	76.9	3.04	41.1	4.00
August		82.1	72.4	3.40	48.4	3.61
Sept.		85.0	74.0	4.40	59.5	2.60

1965 SUMMARY

JAMAICA BAY

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat	5-day BOD
June	J_1	92.0	64.3	6.63	82.10	3.12
July		88.0	69.5	6.26	81.22	2.05
August		88.8	73.4	5.81	78.88	1.94
June	J_2	89.2	67.0	7.33	92.95	4.03
July		85.8	72.5	5.87	78.28	3.11
August		86.3	74.1	5.83	80.92	2.65
June	J_3	88.7	68.3	6.53	85.58	4.40
July		86.2	73.7	4.99	68.13	2.93
August		85.8	74.4	5.05	69.36	3.06
June	J_5	86.8	68.2	6.73	85.65	3.58
July		86.7	73.3	4.84	65.55	1.91
August		87.1	75.0	3.88	52.15	1.44
June	J_7	83.3	69.3	4.77	61.33	4.27
July		85.2	74.5	3.06	49.18	3.27
August		80.6	76.8	4.70	64.48	4.36

HARLEM RIVER

1954 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm		Top and Bottom Averages		
		top	bottom	top & bottom	top	bottom	top	bottom	% Sea	D. O.	BOD
H_1	1	26	36	64	6.8	5.1	1.9	1.3	31	6.95	1.6
	2	34	40	70	3.8	3.1	1.1	1.2	37	3.45	1.15
	3	50	53	74	3.7	3.4	1.5	1.2	51.5	3.55	1.35
	4	55	55	70	3.0	2.9	1.5	1.3	55	2.95	1.4
H_2	1	31	34	65	6.0	6.2	1.7	1.7	32.5	6.1	1.7
	2	42	43	70	3.5	3.4	1.0	0.9	42.5	3.45	0.95
	3	57	58	74	3.0	3.0	1.5	1.3	57.5	3.0	1.4
	4	55	54	71	3.1	3.1	1.6	1.2	54.5	3.1	1.4
H_3	1	54	55	64	4.5	4.4	1.5	1.7	54.5	4.45	1.6
	2	60	61	70	2.5	2.5	1.2	1.1	60.5	2.5	1.15
	3	68	68	74	2.1	2.1	1.5	1.5	68	2.1	1.5
	4	55	56	72	3.3	3.2	1.5	1.6	55.5	3.25	1.55
H_4	1	59	59	61	3.3	3.5	1.5	1.5	59.	3.4	1.5
	2	66	69	69	1.9	1.9	1.4	1.2	67.5	1.9	1.3
	3	76	77	73	1.4	1.5	1.8	1.8	76.5	1.45	1.8
	4	66	69	71	2.5	2.2	1.5	1.0	67.5	2.35	1.25
H_5	1	65	59	62	2.6	4.4	2.2	2.6	67	3.5	2.4
	2	74	75	68	1.9	2.1	1.7	2.7	75	2.0	2.2
	3	80	81	72	1.5	1.5	2.2	2.1	80.5	1.5	2.15
	4	80	80	70	2.1	2.1	2.3	3.5	80	2.1	2.9

HARLEM RIVER

1955 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
H_1	1	43	44	68	3.6	3.4	1.8	1.2
	2	46	54	76	3.8	2.8	2.0	1.6
	3	37	43	70	3.1	2.2	1.8	1.3
	4	42	42	71	2.7	2.8	1.6	1.5
H_2	1	51	54	68	2.6	2.4	1.6	1.3
	2	55	55	76	3.1	3.0	2.2	1.3
	3	46	48	78	2.9	2.8	2.0	1.3
	4	56	58	72	2.7	2.8	1.7	1.3
H_3	1	63	67	67	2.2	2.3	2.1	1.5
	2	64	67	75	2.0	2.2	2.2	2.2
	3	57	59	78	2.0	2.2	2.1	1.5
	4	56	58	72	2.1	2.2	2.2	1.4
H_4	1	75	76	66	2.0	2.1	2.2	1.8
	2	76	76	73	1.4	1.6	1.8	1.2
	3	68	69	77	1.3	1.4	2.2	1.6
	4	70	71	72	1.5	1.6	1.6	1.9
H_5	1	76	79	65	2.4	2.6	3.5	2.5
	2	78	80	71	1.2	1.1	3.7	2.8
	3	75	78	75	1.1	1.2	2.8	2.2
	4	72	72	71	1.5	1.3	4.4	2.5

HARLEM RIVER

1956 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
H_1	1	31	30	68	5.6	5.5	2.1	1.4
	2	42	46	72	3.9	3.3	2.1	1.6
	3	48	51	74	2.4	3.0	3.2	2.2
	4	38	46	69	4.8	3.5	2.9	1.5
H_2	1	29	29	68	5.5	5.2	1.8	1.9
	2	46	45	72	3.4	3.6	2.2	1.4
	3	52	55	75	2.5	2.8	3.5	2.4
	4	44	47	69	3.6	3.7	2.4	1.4
H_3	1	43	43	67	4.8	4.7	2.7	1.9
	2	48	48	72	3.2	3.3	1.9	1.6
	3	61	62	74	1.8	2.0	3.6	2.3
	4	63	64	70	2.2	2.3	3.0	1.3
H_4	1	50	51	67	3.9	4.0	2.4	2.2
	2	59	61	70	2.4	2.6	2.0	1.6
	3	70	72	73	1.3	1.5	3.5	2.5
	4	72	72	70	1.4	1.7	2.4	1.1
H_5	1	60	65	66	4.7	3.9	4.4	4.4
	2	70	73	69	1.0	2.0	3.3	1.9
	3	73	75	73	1.1	1.5	3.5	2.4
	4	71	74	69	1.6	1.8	2.2	1.3

HARLEM RIVER

1957 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
H_1	1	40	47	75	4.4	3.3	3.6	1.7
	2	48	51	75	4.6	3.8	2.2	1.4
	3	51	58	75	3.8	2.8	2.5	1.6
	4	49	55	70	4.7	3.5	3.4	1.8
H_2	1	47	51	73	3.6	3.2	3.2	2.0
	2	54	57	75	3.2	3.2	1.9	0.9
	3	62	63	75	2.5	2.6	2.2	1.3
	4	63	64	71	2.8	3.4	3.1	1.8
H_3	1	64	64	73	2.2	2.2	2.6	2.1
	2	59	61	75	3.0	3.3	1.9	1.3
	3	69	72	75	1.8	2.1	1.9	1.5
	4	72	74	71	2.1	2.2	2.7	1.9
H_4	1	73	76	71	2.0	2.2	2.8	1.7
	2	68	73	74	2.2	1.9	2.0	1.1
	3	77	79	74	1.6	1.7	1.7	1.5
	4	77	78	72	2.1	2.4	2.7	1.8
H_5	1	70	76	71	1.9	2.1	5.3	2.1
	2	75	80	73	1.6	1.7	2.7	1.6
	3	80	83	74	1.7	1.6	2.9	2.2
	4	80	81	69	2.0	2.2	3.7	2.1

HARLEM RIVER

1958 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
H_1	1	31	36	65	4.7	4.8	2.1	1.7
	2	42	49	74	4.3	3.7	1.9	1.7
	3	40	45	75	4.2	3.7	2.0	1.5
	4	45	48	71	3.9	4.0	1.8	1.2
H_2	1	49	50	65	3.9	4.3	3.2	1.7
	2	51	54	74	3.5	3.4	2.3	1.2
	3	40	42	74	4.0	4.2	2.5	1.6
	4	50	52	72	3.6	4.2	1.8	1.1
H_3	1	54	53	64	3.7	4.0	2.2	1.6
	2	66	67	72	2.4	3.0	1.6	1.0
	3	59	59	74	2.7	2.9	2.2	1.5
	4	64	66	71	2.6	2.9	1.4	1.0
H_4	1	61	64	63	3.4	3.6	3.0	1.5
	2	71	73	70	2.4	2.7	1.9	1.1
	3	72	73	73	1.6	2.1	2.8	1.6
	4	72	75	70	2.3	2.3	1.3	0.8
H_5	1	67	71	63	3.3	3.6	4.4	2.5
	2	72	74	71	2.5	2.7	2.7	1.4
	3	72	75	72	1.7	1.9	3.6	2.0
	4	74	76	70	2.0	2.4	2.8	1.2

HARLEM RIVER

1959 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
H_1	1	42	42	69	4.4	4.4	1.7	1.6
	2	44	46	74	3.4	3.5	1.4	1.2
	3	52	55	66	3.2	2.6	1.8	1.4
	4	54	56	71	3.3	2.9	1.8	1.3
H_2	1	44	46	70	3.7	4.1	1.7	1.4
	2	45	46	74	3.2	3.8	1.2	1.5
	3	57	58	78	2.4	2.5	1.3	1.4
	4	57	57	71	2.9	3.2	1.4	1.3
H_3	1	56	56	69	3.0	3.3	1.9	2.0
	2	55	56	77	2.4	3.0	1.3	1.5
	3	67	68	77	1.8	2.0	1.7	1.6
	4	62	61	70	2.8	2.9	1.5	1.7
H_4	1	64	67	68	2.5	2.9	2.2	2.1
	2	68	70	72	1.4	1.8	1.5	1.7
	3	77	78	76	1.3	1.4	2.3	2.1
	4	68	71	70	2.4	2.5	1.9	1.5
H_5	1	73	74	67	2.1	2.5	2.1	2.1
	2	72	76	72	1.3	1.5	1.6	2.0
	3	79	82	76	1.5	1.7	2.7	2.3
	4	80	81	70	2.0	1.8	2.5	2.6

1959 SUMMARY

HARLEM RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		41.6	68.8	4.25	49.8	1.58
July	H	42.3	75.3	3.40	43.2	1.50
August	1	48.8	76.7	3.41	44.2	1.20
Sept.		56.6	74.1	2.77	35.4	1.28
June		41.6	69.4	4.40	52.2	1.64
July	H	46.5	75.3	3.00	38.3	1.60
August	2	57.6	77.1	2.21	29.5	1.32
Sept.		57.4	74.4	2.88	37.0	1.87
June		50.9	69.4	3.52	42.9	2.09
July	H	58.7	73.1	1.69	30.8	1.56
August	3	64.8	75.3	1.93	25.2	1.37
Sept.		62.7	73.0	2.51	31.1	1.72
June		63.5	67.3	2.93	35.5	2.35
July	H	70.1	72.5	1.63	21.0	1.81
August	4	75.6	74.5	1.01	13.4	1.33
Sept.		72.8	72.9	2.09	27.1	1.96
June		74.1	66.3	2.54	31.3	2.28
July	H	73.6	73.7	1.42	18.3	2.28
August	5	78.0	74.2	0.88	11.8	1.57
Sept.		81.0	73.0	1.83	24.3	2.58

HARLEM RIVER

1960 SUMMARY SHEET

Station	Period	% Seawater		Temperature	Dissolved O_2		BOD 5-day ppm	
		top	bottom	top & bottom	top	bottom	top	bottom
H_1	1	29	33	69	4.9	4.8	1.3	1.3
	2	33	37	72	3.7	3.5	1.5	1.0
	3	47	45	74	3.2	3.3	1.6	1.2
	4	39	43	76	3.5	3.2	2.1	1.0
H_2	1	29	29	69	5.2	5.2	1.2	1.4
	2	35	36	72	3.7	3.6	2.2	1.0
	3	53	53	78	2.9	2.9	1.7	1.1
	4	52	51	77	2.3	2.8	2.0	2.0
H_3	1	57	59	67	2.9	2.8	1.9	1.9
	2	48	50	71	2.8	2.8	1.7	1.0
	3	52	54	74	2.5	2.9	2.5	2.6
	4	55	56	76	2.4	2.7	2.5	1.9
H_4	1	69	66	66	2.2	2.3	2.7	1.5
	2	65	65	70	2.1	2.0	1.9	1.2
	3	66	67	73	1.8	2.1	2.5	1.5
	4	66	68	75	1.7	2.3	2.6	2.1
H_5	1	69	71	67	2.7	2.8	3.3	2.1
	2	70	72	69	2.1	2.1	3.3	2.5
	3	74	75	72	1.7	1.7	3.9	2.3
	4	70	73	75	1.3	1.7	2.8	2.4

1960 SUMMARY

HARLEM RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	H 1	32.0	70.0	4.30	50.5	1.20
July		44.9	73.6	3.30	56.4	1.57
August		40.6	75.0	3.36	42.1	1.48
Sept.		40.5	75.7	3.27	40.2	--
June	H 2	29.0	70.0	4.60	48.2	2.30
July		49.9	74.1	3.20	40.7	1.41
August		53.1	75.9	2.28	29.0	1.92
Sept.		54.9	76.9	2.56	31.1	--
June	H 3	51.0	69.0	2.90	34.6	1.80
July		52.8	73.4	2.79	35.4	2.40
August		54.8	74.5	2.61	32.9	2.17
Sept.		69.0	76.1	2.27	29.7	--
June	H 4	64.0	68.0	2.10	25.5	2.20
July		67.7	71.9	2.16	27.2	1.75
August		64.4	73.8	2.01	26.2	2.46
Sept.		70.6	74.6	1.85	24.5	--
June	H 5	69.0	68.0	2.40	29.9	3.40
July		74.6	71.2	1.91	24.6	2.87
August		72.2	74.0	1.43	19.0	3.04
Sept.		71.4	75.1	1.58	21.1	--

HARLEM RIVER

1961 SUMMARY SHEET

Station	Period	% Seawater top	% Seawater bottom	Temperature top & bottom	Dissolved O_2 top	Dissolved O_2 bottom	BOD 5-day ppm top	BOD 5-day ppm bottom
H_1	1	22	29	69	6.9	5.1	1.9	2.0
	2	35	37	73	4.3	3.7	2.0	1.6
	3	44	46	77	3.4	3.0	1.3	1.5
	4	46	43	79	3.1	3.0	0.5	0.7
H_2	1	33	34	69	5.3	4.8	2.4	2.6
	2	32	30	73	4.1	4.3	1.6	1.1
	3	47	47	77	3.0	3.1	1.4	1.5
	4	40	39	79	3.6	3.6	0.7	0.1
H_3	1	49	50	68	3.8	3.4	3.5	2.4
	2	53	54	71	2.9	2.6	2.4	1.9
	3	57	58	76	2.4	2.3	2.1	2.0
	4	39	38	79	3.6	3.7	0.9	0.7
H_4	1	60	60	66	3.4	2.9	3.4	2.9
	2	66	68	70	3.4	2.1	2.7	2.4
	3	63	66	75	1.5	1.5	2.4	1.9
	4	54	60	78	2.4	1.7	1.0	2.1
H_5	1	66	69	66	3.3	2.7	3.2	3.4
	2	70	69	69	2.6	2.5	3.6	3.1
	3	72	73	75	1.6	1.6	2.5	2.0
	4	68	69	77	1.6	1.1	1.7	4.2

1961 SUMMARY

HARLEM RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	H_1	25.3	68.4	5.90	69.3	1.64
July		38.3	74.3	3.90	49.6	1.42
August		47.4	76.9	2.76	37.0	.83
Sept.		42.0	81.0	2.70	56.0	0.0
June	H_2	33.1	69.1	5.08	61.6	2.05
July		35.5	75.1	3.83	47.6	1.12
August		48.6	77.4	2.83	36.9	.80
Sept.		41.0	80.0	4.35	58.0	1.00
June	H_3	49.4	67.6	3.51	41.6	2.68
July		54.1	73.7	2.54	31.3	1.75
August		53.0	76.7	2.73	34.8	.78
Sept.		47.0	80.0	3.30	44.0	0.00
June	H_4	49.9	66.4	3.17	37.2	3.12
July		65.5	69.2	2.06	23.7	2.30
August		61.3	76.2	1.81	24.1	1.58
Sept.		68.0	79.5	1.60	22.5	0.35
June	H_5	66.1	65.6	3.30	36.1	3.52
July		69.9	71.6	1.82	24.8	2.83
August		64.4	75.5	1.49	24.6	2.33
Sept.		73.0	77.0	1.85	25.5	1.60

1962 SUMMARY

HARLEM RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	H_1	48.2	71.0	3.10	38.3	2.96
July		52.8	74.1	3.49	44.5	1.69
August		53.8	75.7	3.67	47.6	1.11
Sept.		58.3	73.5	2.88	37.0	
June	H_2	51.5	71.1	2.90	35.3	2.81
July		61.9	74.8	2.57	33.3	1.90
August		52.3	75.3	3.74	48.8	1.35
Sept.		53.0	73.5	3.30	42.0	
June	H_3	53.9	70.4	3.10	37.7	2.41
July		63.9	73.3	2.45	31.4	1.55
August		66.6	75.3	2.18	28.9	1.47
Sept.		62.0	73.3	1.75	22.6	
June	H_4	63.4	69.9	2.21	24.7	2.28
July		71.7	72.9	1.72	22.5	2.05
August		76.1	74.6	1.43	1.91	1.75
Sept.		73.8	74.0	1.35	1.80	
June	H_5	71.1	69.1	1.90	23.8	2.16
July		76.5	72.4	1.67	22.0	2.18
August		79.3	74.4	1.23	16.6	1.75
Sept.		77.8	73.8	1.03	13.7	

1963 SUMMARY

HARLEM RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	H_1	43.8	69.8	3.63	43.5	1.84
July		51.3	75.3	3.60	49.3	1.73
August		58.7	74.8	3.60	47.0	1.74
Sept.		54.5	71.3	2.93	40.3	1.50
June	H_2	51.8	69.7	3.39	43.0	1.78
July		56.7	75.6	3.09	40.1	1.72
August		55.0	74.9	3.24	41.3	1.51
Sept.		63.3	71.3	2.75	36.1	1.50
June	H_3	54.1	69.3	2.93	35.2	2.38
July		61.0	74.8	3.03	39.9	1.64
August		60.7	74.4	2.71	21.6	1.88
Sept.		65.0	70.8	3.00	37.6	1.88
June	H_4	67.2	68.5	1.72	25.5	2.08
July		68.4	73.7	2.31	32.0	1.89
August		73.7	73.3	1.64	20.5	2.20
Sept.		71.8	71.8	2.05	29.4	1.90
June	H_5	72.7	68.9	1.45	18.3	2.28
July		74.1	72.8	2.12	28.4	2.23
August		80.6	72.9	1.71	21.9	2.17
Sept.		79.8	71.8	2.05	26.2	1.95

1964 SUMMARY

HARLEM RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	H_2	50.1	66.4	3.87	43.0	2.45
July		53.9	72.8	3.45	43.9	3.83
August		55.4	73.1	3.26	41.3	3.31
Sept.		65.0	72.8	3.20	41.2	2.43
June	H_3	55.5	65.8	3.19	37.7	2.67
July		60.7	72.5	3.01	38.3	3.86
August		67.2	73.0	3.28	41.8	3.38
Sept.		73.2	73.3	2.47	32.4	2.98
June	H_4	68.2	65.1	2.64	31.7	2.70
July		67.1	71.8	2.07	25.4	3.93
August		72.5	72.3	2.31	30.9	2.75
Sept.		75.3	73.0	2.15	28.3	3.33
June	H_5	71.1	65.4	2.70	32.6	2.95
July		74.5	71.2	1.74	22.4	3.95
August		75.7	72.1	2.11	27.6	3.26
Sept.		76.3	73.2	2.87	37.9	3.60
June	N_9	94.0	62.0	6.47	82.4	2.43
July		90.6	69.4	6.46	84.4	3.68
August		91.4	67.9	6.65	85.7	1.78
Sept.		94.0	70.5	6.30	84.0	2.95

1965 SUMMARY

HARLEM RIVER

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	H_1	51.0	68.1	3.89	46.2	1.53
July		52.1	73.5	3.46	43.9	1.40
August		45.1	75.4	3.34	43.1	1.16
June	H_2	61.0	68.6	2.79	37.8	1.44
July		56.2	73.8	3.39	43.0	1.36
August		57.0	75.1	3.41	42.8	1.33
June	H_3	66.5	67.3	3.33	42.0	1.74
July		70.9	73.3	2.94	37.0	1.33
August		68.6	74.0	1.67	28.8	1.32
June	H_4	68.7	67.6	2.88	34.0	1.94
July		74.4	72.1	1.70	24.1	1.48
August		75.3	74.1	1.57	21.0	1.39
June	H_5	73.9	66.3	2.01	23.9	2.17
July		77.4	72.3	1.59	21.1	1.79
August		79.1	73.7	1.26	15.8	1.63

1954 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Station	Date	Temperature (°F)	Dissolved Oxygen		BOD 5-day ppm	% Seawater	Chlorides
			Sample ppm	% Sat.			
K_1	July	71	3.0	49	1.4	80	16070
K_2	July	74	3.1	41	2.4	74	14800
K_3	July	75	0.6	8	3.3	73	14600
K_4	July	77	2.3	30	2.8	78	15600
K_5	July	75	5.1	70	1.4	83	16670
K_6	July	73	7.4	96	2.1	86	17200
K_8	July	73	4.3	57	2.0	83	16670

1955 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Station	Date	Temperature (°F.)	Dissolved Oxygen Sample ppm	Dissolved Oxygen % Sat.	BOD 5-day ppm	% Seawater	Chlorides
K_1	June	62	4.4	52	1.8	72	14400
K_2	June	65	3.8	46	1.8	68	13500
K_3	June	65	1.8	22	3.6	67	13400
K_4	June	66	0.8	9	4.4	68	13600
K_5	June	66	3.2	40	2.0	76	15300
K_6	June	61	6.2	74	1.6	82	16500

1956 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Station	Date	Temperature (°F.)	Dissolved Oxygen Sample ppm	Dissolved Oxygen % Sat.	BOD 5-day ppm	% Seawater	Chlorides
K_1	August	70	3.0	38	2.1	78	15500
K_2	August	72	2.4	31	3.5	70	14100
K_3	August	74	1.6	20	4.4	69	13800
K_4	August	74	1.9	17	3.6	74	14800
K_5	August	73	4.2	54	2.6	80	15900
K_6	August	73	5.0	67	3.5	85	17000

1957 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill, and Lower New York Bay

Station	Date	Temperature (°F.)	Dissolved Oxygen		BOD 5-day ppm	% Seawater	Chlorides
			Sample ppm	% Sat.			
K_1	June	70	3.7	47	3.4	74	14800
	July	72	3.0	40	3.3	78	15530
	August	72	2.7	36	1.8	82	16300
K_2	June	76	4.1	58	2.2	68	13600
	July	76	3.3	45	3.3	75	15070
	August	76	1.7	22	1.2	76	15100
K_3	June	77	1.2	15	3.6	68	13600
	July	77	1.0	13	4.7	76	17570
	August	76	1.0	13	4.0	75	15000
K_4	June	77	2.1	29	4.3	72	14330
	July	78	1.2	17	4.0	77	17000
	August	77	1.9	26	4.0	80	15900
K_5	June	76	5.0	69	3.7	76	15200
	July	76	4.4	61	2.6	85	15470
	August	76	3.8	53	2.8	84	16800
K_{5a}	June	76	6.0	82	3.4	74	14730
	July	76	4.8	66	2.7	83	16600
	August	76	5.2	72	2.8	84	16800
K_6	June	72	7.7	102	3.3	82	16400
	July	74	6.2	84	2.9	87	17330
	August	73	6.7	90	2.9	88	17500

1958 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill, and Lower New York Bay

Station	Date	Temperature (°F.)	Dissolved Oxygen		BOD 5-day ppm	% Seawater	Chlorides
			Sample ppm	% Sat.			
K_1	June	62	5.0	58	2.3	67	13470
	August	71	3.0	39	1.7	75	15180
K_2	June	66	4.8	57	3.7	58	11530
	August	75	2.4	31	3.0	69	13850
3	June	67	3.0	36	5.0	58	11600
	August	75	1.0	13	4.6	69	13800
K_4	June	69	1.7	21	4.7	60	12070
	August	77	1.6	22	3.6	73	14550
K_5	June	68	4.8	59	2.5	67	13470
	August	75	4.2	56	2.9	80	15900
K_{5a}	June	68	5.1	61	2.0	65	13000
K_6	June	65	7.3	94	2.9	76	15200
	August	74	4.4	59	2.0	76	15250
K_8	August	72	5.8	78	2.7	83	16650

1959 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill, and Lower New York Bay

Station	Date	Temperature (°F.)	Dissolved Oxygen		BOD 5-day ppm	% Seawater	Chlorides
			Sample ppm	% Sat.			
K_1	June	65	4.9	58	2.5	73	14530
	August	73	2.1	28	4.1	78	15700
	Sept.	74	2.1	28	2.2	80	16000
K_2	June	68	3.7	44	2.1	65	13000
	August	76	1.7	23	1.6	66	13200
	Sept.	76	2.9	39	1.5	70	14000
K_3	June	69	2.7	33	2.9	65	12930
	August	77	0.7	9	3.5	69	13750
	Sept.	77	2.2	30	2.7	74	14800
K_4	June	71	3.2	41	2.5	70	14070
	August	77	1.8	24	1.6	73	14600
	Sept.	78	1.6	23	1.9	76	15200
K_5	June	69	3.9	64	2.5	76	15270
	August	75	2.6	35	1.8	76	15100
	Sept.	78	3.0	42	2.1	79	15800
K_{5a}	June	68	5.5	66	4.4	75	14930
	August	75	2.6	36	5.2	75	15050
	Sept.	78	2.7	39	3.0	75	15000
K_6	June	66	7.2	91	2.8	80	15930
	August	75	6.3	86	2.3	87	17400
	Sept.	77	6.1	85	2.1	84	16800

1959 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill, and Lower New York Bay

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		72.8	64.0	4.88	58.2	2.42
July	K	75.5	74.0	2.25	30.0	1.70
August	1	80.1	72.6	2.66	35.4	1.39
Sept.		80.0	74.0	2.50	28.0	2.20
June		65.0	68.2	3.72	45.8	2.13
July	K	70.3	75.5	2.50	33.3	1.85
August	2	69.0	75.0	1.72	23.0	1.51
Sept.		70.0	76.0	2.90	39.0	1.55
June		64.7	68.7	2.68	32.8	2.87
July	K	71.5	73.0	1.55	21.0	2.20
August	3	68.5	76.2	0.74	9.8	2.28
Sept.		73.5	77.0	2.15	29.5	2.70
June		70.5	70.8	3.20	40.7	2.52
July	K	73.0	74.5	1.00	14.0	2.10
August	4	74.0	76.5	1.88	26.0	1.58
Sept.		76.0	78.5	1.60	22.5	1.85
June		76.3	68.7	5.03	63.8	2.50
July	K	74.3	76.8	2.58	35.3	1.30
August	5	72.3	74.8	3.00	40.6	1.33
Sept.		79.0	77.5	3.05	42.0	2.15
June		74.8	67.5	5.28	66.0	4.38
July	K	77.0	76.0	2.93	40.0	3.55
August	5a	78.8	75.0	3.11	42.3	3.43
Sept.		75.5	78.0	2.75	38.5	3.05
June		80.2	66.0	7.25	90.8	2.85
July	K	85.5	73.3	5.83	98.0	2.28
August	6	87.5	74.3	5.93	81.3	2.01
Sept.		84.5	77.0	6.10	85.0	2.05

1960 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill, and Lower New York Bay

Station	Date	Temperature (°F.)	Dissolved Oxygen Sample ppm	Dissolved Oxygen % Sat.	BOD 5-day ppm	% Seawater	Chlorides
K_1	July	70	3.2	40.4	1.7	73	14670
K_2	July	74	3.8	49.4	2.4	68	13530
K_3	July	76	1.7	22.2	2.9	70	13930
K_4	July	78	1.8	24.8	3.0	70	13930
K_5	July	76	3.8	52.0	2.8	75	15000
K_{5a}	July	75	4.1	52.8	4.6	76	15270
K_6	July	71	6.9	95.0	4.3	84	16730

1960 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		70.0	66.0	3.80	45.4	1.20
July	K	75.5	69.5	3.30	41.9	1.45
August	1	66.5	74.2	2.55	33.5	1.33
Sept.		80.0	71.3	3.13	40.9	.93
June		64.0	68.0	3.50	37.3	1.49
July	K	69.8	72.8	3.65	47.3	2.83
August	2	55.3	75.6	1.28	28.8	1.95
Sept.		69.5	73.3	2.00	26.1	2.33
June		62.0	71.0	1.50	18.9	2.00
July	K	68.8	75.3	1.73	35.2	2.73
August	3	56.6	76.7	.86	11.5	2.93
Sept.		65.5	76.5	.38	5.2	3.53
June		66.0	72.0	1.50	20.3	2.40
July	K	70.5	71.0	1.62	22.6	2.95
August	4	60.8	79.9	.85	18.0	1.98
Sept.		70.0	76.0	1.18	16.0	2.10
June		74.0	71.0	4.70	58.0	2.10
July	K	76.5	74.8	3.78	51.1	2.08
August	5	74.8	77.8	2.80	38.3	1.45
Sept.		74.5	74.0	3.15	41.7	1.50
June		79.0	67.0	5.80	72.5	2.80
July	K	83.8	77.6	5.92	84.1	3.02
August	6	79.1	78.0	5.90	80.7	2.85
Sept.		83.3	72.8	5.92	78.9	2.93
June		72.0	71.0	4.80	58.5	3.50
July	K	77.5	74.3	3.85	51.3	3.78
August	5a	71.2	76.8	2.73	37.1	2.93
Sept.		72.3	75.0	2.83	35.4	4.40

1961 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June		63.8	69.9	.98	12.6	4.73
July	K	66.0	76.8	1.45	19.3	2.20
August	4	61.5	80.1	.86	5.5	3.44
Sept.		71.5	80.5	2.50	3.3	0.90
June		74.5	68.5	4.59	58.0	3.18
July	K	76.3	75.5	4.98	66.5	2.38
August	5	68.8	77.0	3.81	51.0	1.34
Sept.		78.3	78.5	2.10	29.5	2.30
June		70.8	70.3	4.51	55.6	4.83
July	K	73.8	73.8	4.88	64.5	4.50
August	5a	69.5	76.0	3.26	43.6	1.34
Sept.		74.5	77.8	2.68	36.8	4.75
June		78.8	65.3	6.96	85.4	3.20
July	K	77.8	74.0	7.63	101.5	3.13
August	6	83.1	76.0	5.59	77.4	1.34
Sept.		83.5	83.5	6.48	90.5	2.60
June		90.5	61.4	7.78	94.5	2.23
July	N	91.2	70.5	7.13	93.8	0.90
August	9a	93.8	71.1	6.38	83.8	0.77
Sept.		90.0	72.3	5.70	76.8	2.75

1962 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill, and Lower New York Bay

Station	Date	Temperature (°F.)	Dissolved Oxygen Sample ppm	Dissolved Oxygen % Sat.	BOD 5-day ppm	% Seawater	Chlorides
K_1	July	72	3.4	43.8	1.8	79	15850
	Sept.	73	1.8	23.6	1.9	74	14800
K_2	July	74	3.3	44.2	3.8	76	15150
	Sept.	75	1.7	22.7	0.9	7.2	14400
K_3	July	76	1.0	14.0	3.8	73	14600
	Sept.	79	0.2	2.8	4.3	74	14800
K_4	July	76	2.1	26.7	4.2	72	14500
	Sept.	78	1.0	13.8	3.5	72	14400
K_5	July	74	4.7	63.8	3.3	80	15900
	Sept.	75	3.7	50.2	1.6	79	15800
K_{5a}	July	74	5.0	79.9	4.9	75	14950
	Sept.	74	3.1	41.3	5.3	74	14800
K_6	July	73	9.0	122.1	4.2	89	17850
	Sept.	74	4.4	60.4	2.1	91	18200

1962 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	K_1	76.0	66.5	3.57	40.5	1.43
July		81.4	70.6	4.75	49.0	1.80
August		84.1	73.5	2.74	37.0	3.13
Sept.		74.0	72.5	1.80	23.5	1.35
June	K_2	70.2	70.0	3.52	43.1	1.77
July		75.3	73.1	4.35	39.6	3.16
August		77.9	75.1	2.06	32.1	2.79
Sept.		72.0	75.0	1.55	20.7	1.10
June	K_3	69.3	72.3	1.45	21.9	3.82
July		73.8	75.6	2.88	32.4	3.61
August		75.1	75.5	1.16	15.7	3.28
Sept.		73.0	78.0	0.20	2.8	3.95
June	K_4	69.7	72.7	1.38	18.1	3.50
July		76.0	76.4	2.52	37.7	3.56
August		77.3	77.3	.96	13.3	3.14
Sept.		73.5	77.0	0.75	10.3	2.70
June	K_5	77.5	70.8	3.92	51.4	1.93
July		80.0	74.5	5.54	65.8	3.05
August		84.5	75.5	1.37	51.8	2.61
Sept.		81.0	74.5	3.45	46.7	3.60

1963 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Station	Date	Temperature (°F.)	Dissolved Oxygen		BOD 5-day ppm	% Seawater	Chlorides
			Sample ppm	% Sat.			
K_1	July	71	3.0	39.0	2.6	78	15550
K_2	July	72	3.2	42.5	3.9	76	15150
K_3	July	74	2.2	30.2	4.8	74	14700
K_4	July	77	1.4	18.3	3.6	78	15050
K_5	July	76	4.6	58.8	2.8	83	16600
K_{5a}	July	75	4.7	61.2	6.0	80	16100
K_6	July	73	10.4	146.4	4.0	84	16700

1963 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	K_1	71.0	67.0	2.63	32.5	2.40
July		81.3	70.0	3.33	41.4	2.31
August		82.9	71.0	3.55	46.4	2.11
Sept.		83.3	69.3	3.33	45.3	1.78
June	K_2	67.8	69.8	2.38	30.3	3.20
July		76.5	71.9	2.79	36.5	2.97
August		77.6	73.6	3.19	41.8	2.61
Sept.		80.0	72.3	2.45	32.2	2.38
June	K_3	69.2	71.3	1.33	17.3	5.00
July		73.9	75.4	1.64	22.3	4.47
August		78.1	75.8	1.16	16.8	4.66
Sept.		76.5	73.5	1.18	15.4	4.00
June	K_4	71.8	74.3	.87	9.7	4.70
July		75.6	76.8	1.26	15.5	3.23
August		78.6	77.5	1.18	15.8	2.98
Sept.		83.0	73.8	1.65	22.2	4.03
June	K_5	75.7	71.7	5.67	61.7	3.53
July		83.1	75.4	1.10	62.5	2.60
August		86.3	76.1	4.05	56.3	3.34
Sept.		86.8	72.8	4.20	56.5	2.53

1964 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	K_1	75.7	64.0	3.60	43.3	2.45
July		78.2	72.3	3.50	46.4	2.67
August		78.3	71.1	2.39	29.8	3.44
Sept.		77.0	72.8	3.38	44.6	2.88
June	K_2	69.7	66.3	3.18	38.8	2.70
July		71.8	74.8	1.78	23.8	3.05
August		74.3	72.4	2.48	31.6	3.34
Sept.		74.8	74.0	2.70	40.9	3.00
June	K_3	68.8	67.7	2.27	28.0	3.47
July		70.3	76.5	.25	4.0	4.26
August		72.1	74.5	1.00	13.1	4.48
Sept.		75.3	76.5	.90	12.3	3.70
June	K_4	69.5	70.3	1.03	13.3	3.30
July		72.8	77.3	1.25	17.1	3.15
August		75.1	76.3	1.03	14.0	4.34
Sept.		77.0	78.8	.80	11.3	5.80
June	K_5	79.2	68.8	4.17	54.0	2.33
July		78.7	75.0	3.48	51.4	3.14
August		80.5	73.4	4.06	54.2	4.37
Sept.		82.5	76.3	3.53	48.2	2.93

1964 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill and Lower New York Bay

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	K_{5a}	83.3	67.0	4.78	60.7	3.10
July		75.7	74.3	3.35	44.8	----
August		78.6	72.5	3.95	52.0	5.55
Sept.		79.0	75.0	3.03	38.9	4.63
June	K_6	83.8	65.2	8.75	109.6	2.87
July		85.2	73.7	6.45	87.6	3.82
August		85.5	71.0	7.11	93.4	4.40
Sept.		80.8	74.3	8.58	116.7	3.25
June	N_6	79.5	63.0	4.27	51.0	2.75
July		79.7	71.6	3.32	43.7	2.28
August		80.0	70.6	3.45	44.6	2.83
Sept.		80.7	72.2	4.38	57.8	3.33
June	N_7	79.0	63.0	4.26	51.1	3.10
July		78.5	66.7	2.92	38.0	2.99
August		77.4	70.6	2.81	36.4	3.39
Sept.		78.0	72.3	4.82	63.3	----
June	N_8	82.8	64.5	4.73	58.7	2.38
July		82.6	71.4	4.51	59.3	3.23
August		83.4	70.9	5.43	72.0	4.95
Sept.		83.5	73.0	5.10	68.3	3.03

1965 SUMMARY

Kill Van Kull, Newark Bay, Arthur Kill, and Lower New York Bay

Date	Station	% Seawater	Temperature	Dissolved O_2	% Sat.	5-day BOD
June	K 1	83	65	4.2	51.9	1.7
July		84	70	3.1	40.5	2.4
August		78	73	2.2	29.1	1.2
Sept.		78	69	4.2	53.0	2.1
June	K 2	79	68	3.2	37.2	1.6
July		82	74	1.9	34.7	2.6
August		79	76	1.3	13.7	3.8
Sept.		75	70	1.7	21.3	2.6
June	K 3	77	69	1.3	16.6	1.7
July		82	77	0.7	13.5	4.2
August		77	77	0.2	3.7	5.2
Sept.		75	73	1.1	17.2	3.4
June	K 4	79	72	1.2	17.0	3.0
July		84	78	0.8	11.6	4.2
August		82	80	0.7	9.7	4.8
Sept.		78	73	0.9	7.2	4.6
June	K 6	88	67	7.1	89.6	2.9
July		87	72	6.0	86.3	2.3
August		89	74	7.2	98.3	3.9
Sept.		87	70	5.6	97.0	2.7